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# POWER SYSTEMS FOR FUTURE MISSIONS

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LeRC Group
Brookpark, OH 44142
Under Contract LG-2545

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Space Administration

# POWER SYSTEMS FOR FUTURE MISSIONS

CONTRACT LG2545

FINAL REPORT

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# NOMENCLATURE

| | | |
|---|---|---|
| BIPS | = | Brayton Isotope Power System |
| BOL | = | Beginning of Life |
| BRU | = | Brayton Rotating Unit |
| C-C | = | Carbon-Carbon |
| $C_B$ | = | Reboost Cost |
| CBC | = | Closed Brayton Cycle |
| $C_D$ | = | Development Cost |
| CERs | = | Cost Estimating Relationships |
| CIS | = | Copper Indium Diselenide |
| $C_P$ | = | Production Cost |
| $C_{PP}$ | = | Flight Hardware Cost of One Space Power System |
| $C_R$ | = | Replacement Cost |
| $C_T$ | = | Transportation Cost |
| $C_U$ | = | Flight Unit Cost |
| $DC_{DP}$ | = | Delta Space Power System Development Cost |
| DDT&E | = | Design, Development, Testing and Engineering |
| DIPS | = | Dynamic Isotope Power System |
| EOM | = | End-Of-Mission |
| EPS | = | Electrical Power System |
| FLO | = | First Lunar Outpost |
| FT | = | Far Term |
| FU | = | Flight Unit |
| GaAs/Ge | = | Gallium Arsenide on Germanium Base Photovoltaic Cell |
| GEO | = | Geosychronous Orbit |
| GES | = | Ground Engineering System |
| GPHS | = | General Purpose Heat Source |
| HP | = | High Pressure |
| HRS | = | Heat Rejection Subsystem |
| HSU | = | Heat Source Unit |
| ISTU | = | Integrated System Test Unit |
| LCC | = | Life Cycle Cost |
| LEO | = | Low Earth Orbit |
| LMCR | = | Liquid Metal Cooled Reactor |
| LMR | = | Liquid Metal Reactor |
| $L_P$ | = | Platform Mission Life |
| $L_S$ | = | Subsystem Life |
| MFI | = | Multifoil Insulation |
| MT | = | Mid Term |
| NaS | = | Sodium Sulfur |
| $N_P$ | = | Number of Modules with Different Power Levels |
| NT | = | Near Term |
| OSR | = | Optical Solar Reflector |
| PCCU | = | Power Conditioning and Control Unit |
| PCU | = | Power Conversion Unit |
| PEM | = | Proton Exchange Membrane |
| PMG | = | Permanent Magnet Generator |
| PP&C | = | Power Processing and Control |
| PPCA | = | Power Processing Control and Assembly |
| PV | = | Photovoltaic |
| QU | = | Qualification Unit |

| | | |
|---|---|---|
| RFC | = | Regenerative Fuel Cell |
| RHRS | = | Reversible Heat Rejection System |
| SC | = | Stirling Cycle |
| SEI | = | Space Exploration Initiative |
| SSF | = | Space Station Freedom |
| TAC | = | Turboalternator Compressor |
| TE | = | Thermoelectric |
| TFE | = | Thermionic Fuel Element |
| TPTL | = | Two Pole Toothless |
| TRL | = | Technical Readiness Level |

## INTRODUCTION AND SUMMARY

Selection of power system technology for space applications is typically based on mass, readiness of a particular technology to meet specific mission requirements, and life cycle costs (LCC). The LCC is typically used as a discriminator between competing technologies for a single mission application. All other future applications for a given technology are usually ignored. As a result, development cost of a technology becomes a dominant factor in the LCC comparison. Therefore, it is common for technologies such as DIPS and LMR-CBC to be potentially applicable to a wide range of missions and still lose out in the initial LCC comparison due to high development costs.

New technologies are developed only when existing technologies are no longer able to meet the requirements or, in some rare cases, when the advantage of new technologies is overwhelming. This approach tends to delay development of new technologies which, if developed, could compete with present technologies. There is a potential for cost reduction in the long run if such technologies that will capture many of these missions are developed.

In this study, the LCC for a set of potential missions is compared for a comprehensive evaluation of economic benefits of current and future power system technologies. The emphasis here is to arrive at a good approach for such an evaluation. It is expected to eventually lead to even more acceptable methods for comparison and provide a basis for long range planning for technology development strategies and, ultimately, to lower cost solution for future power systems.

This study used the results of the Space Station Evolutionary Power (SSEP) Technology Study (NAS3-24902) completed earlier and provides more depth and rationale to the conclusions in the SSEP study (Ref. 1). This study is divided into three major tasks.

Task 1 consists of developing a realistic scenario from the 69 space platforms identified in Tasks 1A, 2, and 2A of the SSEP study (Ref.1) and the additional SEI related missions identified in the NASA 90-day study (Ref. 2) and the Synthesis committee report (Ref. 3). The scenario reflects an aggressive mission profile maximizing the number of missions captured. Power technologies are selected for this scenario based on conclusions of Task 1C of the SSEP study. In addition, In-core Thermionic and Radioisotope Stirling systems, which were not considered in the SSEP study, are included where applicable.

All the 83 missions in this scenario were used to arrive at technology requirements and to identify top level technology goals in terms of operating temperatures and specific power ratings for future missions. Related technology development plans were developed under Task 2 of this study.

Life Cycle Costs (LCC) were determined for the more promising technologies for the mission scenario. The LCC consisted of development cost, production cost, transportation cost, and operational and replacement costs. Benefits of past inheritance, if any, of a given technology were considered. The drag makeup costs for all non-nuclear power systems in LEO missions were also included. LCC models for different power system technologies were then developed and results from a spreadsheet of the DIPS/CBC LCC model were produced.

In Task 2, technology development roadmaps were prepared for each promising technology (see Appendices A-K). Technology system/subsystem maturity levels were assessed for each screened concept and hardware production requirements were estimated (Task 2.1). Major technology issues and gaps were identified (Task 2.2) and current and past programs on related technology were identified (Task 2.3). Technology and hardware development times and schedules were determined and technology development plans were generated (Task 2.4).

In Task 3, a relational database code previously developed for LeRC to perform scheduling and summations of power requirements for Earth-orbital, lunar, and manned Mars missions was converted to a faster and more versatile computer code. This conversion was accomplished using the TREES-pls language and the FOREST-pls scheduling utility library developed by Information Sciences, Inc. The resulting software operates on an Apollo DN3000/4000 workstation. The developed code (named ESPPRS - Ref.3) was verified using test data sets from the SSEP Technology Study to validate that the code capabilities were operational and correct. The code conversion provides NASA with a capability equivalent to the previous version of the database code in basic approach, but with a broader and faster applications base. Also, some enhanced capabilities were added to the ESPPRS version of the code which were not available with the previous version.

# TASK 1.0 TECHNOLOGY REQUIREMENTS AND LIFE CYCLE COST (LCC)

The main objective of this task was to develop a simple methodology to determine LCC of different power systems used on a number of future missions. The task consisted of developing a comprehensive scenario of future missions, assessing applicability of technologies to these missions, and determining LCC of these technologies when development costs are spread over all applicable missions spanning different power levels and timeframes.

The following five subtasks were included in Task 1:

- 1.1 Mission Scenario Identification
- 1.2 Technology Requirements
- 1.3 Life Cycle Cost Analysis
- 1.4 LCC Spreadsheet
- 1.5 LCC and Technology Assessment Results

The scenario development (Subtask 1.1) started with an aggressive mission scenario developed in the SSEP Technology Study (Ref. 1). Then, the SEI related missions obtained from NASA 90-day study (Ref. 2) and the Synthesis committee report (Ref. 3) were added to this scenario. This resulted in a mission scenario consisting of 83 space platforms or mission elements from low Earth orbit (LEO), lunar, and Mars regions.

Subtask 1.2 consisted of identifying the power requirements in terms of power levels, performance goals, timeframes, and technologies to meet these requirements. Based on a cursory evaluation, promising technologies were selected and development requirements and goals were established. Power system concepts were then defined for each mission.

Life Cycle Costs (LCC) (Subtask 1.3) were subsequently determined for power systems using the technologies selected in the previous subtask. The LCC includes development cost, production cost, transportation cost, replacement cost, reboost cost and the cost benefits of any prior technology development.

In Subtask 1.4 a spreadsheet was used to implement the LCC model developed in Subtask 1.3. Results from the application of the LCC model to a DIPS/CBC power system are presented in Subtask 1.5.

## 1.1 MISSION SCENARIO IDENTIFICATION

This subtask identified a scenario consisting of 83 missions based on the 69 space platforms developed in SSEP Study (Ref. 1) and SEI related missions identified in the 90-day study (Ref. 2). In addition, the scenario included recommendations from the Synthesis committee report (Ref. 3). It is a comprehensive list of possible future missions aggressively pursuing future civilian space missions. It includes low to high power (0.1 to 1 MWe) Earth orbital missions and permanent manned occupation of both Moon and Mars. The lunar mission platforms include initial low power lunar outposts that will eventually grow into permanent manned bases with in-situ resource utilization requiring multimegawatts of electric power. Similarly, Mars missions also start as low power outposts eventually growing into permanent manned bases. The mission scenario, shown in Tables 1-1 and 1-2, includes required power level, timeframe, location, and recommended power systems for each mission element (i.e., platform) based on the SSEP study (Ref. 1).

The 34 Earth orbital missions, summarized in Table 1-1, can be characterized as missions to planet Earth with three areas of emphasis. The first area focuses on examining and understanding the Earth's geological, meteorological, and environmental features. The next area consists of service oriented space platforms. These platforms, which include communication, global positioning, and weather service applications, provide basic services that directly enhance terrestrial activities. The last area consists of space-based manufacturing platforms. These platforms consist of man-tended factories and research facilities that either enhance or enable production and processing of materials, crystals, glass fibers, and pharmaceuticals.

All Earth orbital platforms included in the mission scenario were obtained from Task 1A of the SSEP Study. The timeframes of all activities were delayed by four years to reflect an updated Space Station Freedom IOC. The growth of power level for manufacturing platforms was also limited to 1 MWe.

The lunar and Mars missions (Table 1-2) were derived from the SSEP study (Ref. 1). The SSEP Study results formed the basis and the 90-day study (Ref. 2) results added/updated various elements of the lunar and Mars missions. Results from the Synthesis report (Ref. 3) (in particular Architecture III) were used to update the IOC dates from the SSEP study for the lunar and Mars missions.

TABLE 1-1. EARTH ORBITAL MISSION SCENARIO SUMMARY

| PLATFORM / DESCRIPTION | POWER | OPERATIONAL TIME-FRAME | ORBIT LOCATION | POWER SYSTEMS * |
|---|---|---|---|---|
| ***Mission to Planet Earth*** | | | | |
| 1 - Space Station Freedom | 18.75 kWe / TBD | 1999 / TBD | LEO | PV / Battery, SD / CBC, Stirling |
| 2 - Extreme microgravity research laboratory | 108 kWe / 1 MWe | 1999 / 2032 | LEO | SD / CBC, Stirling |
| 3 - Bulk processing/construction facility | 33 kWe / 993 kWe | 1999 / 2050 | LEO | SD / CBC, Stirling |
| 4 - Great observatory 1 | 6.3 / 39.5 kWe | 1996 / 2007 | LEO | PV / Battery, SD / CBC, Stirling |
| 5 - Ocean circulation mission | 0.3 kWe | 1997 | Intermed (1300 km) | PV / Battery |
| 6 - Geopotential Research Mission (GRM) | 0.7 kWe | 1997 | LEO | PV / Battery, SD / CBC, Stirling |
| 7 - Imaging radar and gravity probe facility | 1.2 kWe /16.4 kWe | 1996 / 2013 | Polar | PV / Battery, SD / CBC, Stirling |
| 8 - Fluids testing/propellant facility | 2.1 kWe / 77 kWe | 2002 / 2017 | LEO | PV / Battery, SD / CBC, Stirling |
| 9 - Space Station free flyer (pre-station) | 10.0 kWe | 1996 / 2011 | LEO | PV / Battery, SD / CBC, Stirling |
| 10 - Ultravacuum facility | 88.0 kWe / 206 kWe | 2001 / 2018 | LEO | SD / CBC, Stirling |
| 11 - Med products and pharmaceuticals manuf | 4 kWe / 1 MWe | 2002 / 2014 | LEO | SD / CBC, Stirling |
| 12 - Medium microgravity manufacturing | 16 kWe / 1 MWe | 2006 / 2014 | LEO | SD / CBC, Stirling |
| 13 - Laser heterodyne gravity satellite | 5.6 kWe | 2001 | Heliocentric | PV / Battery, SD / CBC, Stirling |
| 14 - Space Station polar platform | 2.1 kWe | 2001 | Polar | PV / Battery, SD / CBC, Stirling |
| 15 - Geodynamic laser-ranging system | 15.0 kWe / 19.2 kWe | 1997 / 2007 | LEO | PV / Battery, SD / CBC, Stirling |
| 16 - GEO combined platform 1 | 0.8 kWe / 23.9 kWe | 1998 / 2011 | GEO | PV / Battery, SD / CBC, Stirling |
| 17 - Heterodyne laser | 11.2 kWe | 2008 | Heliocentric | PV / Battery, SD / CBC, Stirling |
| 18 - Variable-gravity research facility | 3.2 kWe / 6.4 kWe | 1999 / 2008 | LEO | PV / Battery, SD / CBC, Stirling |
| 19 - Soil, snow, moisture, and precipitation research and assessment satellite | 0.4 kWe / 1.2 kWe | 1996 / 2001 | LEO | PV / Battery, SD / CBC, Stirling |
| 20 - Advanced space science | 0.6 kWe / 3.7 kWe | 2005 / 2012 | LEO | PV / Battery, SD / CBC, Stirling |
| 21 - Seismic monitoring satellite | 10.0 kWe | 2014 | LEO | PV / Battery, SD / CBC, Stirling |
| 22 - Orbiting very long baseline interferometry | 1.9 kWe | 2004 | Intermed (1000 km) | PV / Battery, SD / CBC, Stirling |
| 23 - Space Station co-orbiting platform (free-flyer) | 13.2 kWe | 2004 | LEO | PV / Battery, SD / CBC, Stirling |
| 24 - Remote experiment siting platform for CPPL | 18.7 kWe | 2005 | LEO | PV / Battery, SD / CBC, Stirling |
| 25 - Starprobe science package | 0.7 kWe | 2008 | Heliocentric | PV / Battery, SD / CBC, Stirling |
| 26 - Complementary radiation effects instr. | 0.8 kWe | 2010 | LEO | PV / Battery, SD / CBC, Stirling |
| 27 - Solar seismology platform to augment SSF | 0.1 kWe / 4.9 kWe | 2005 / 2013 | L1 | PV / Battery, SD / CBC, Stirling |
| 28 - Permanent prospector satellite | 10.1 kWe | 2011 | Intermed (2500 km) | PV / Battery, SD / CBC, Stirling |
| 29 - Large glass and crystal form manufacturing | 136 kWe / 1 MWe | 2014 / 2016 | LEO | SD / CBC, Stirling |
| 30 - Advanced communications platform | 10.0 kWe / 320 kWe | 1999 / 2010 | GEO | PV / Battery, SD / CBC, Stirling |
| 31 - Advanced GPS System | 5.0 kWe / 20.0 kWe | 1999 / 2009 | LEO | PV / Battery, SD / CBC, Stirling |
| 32 - Global Air and Sea Traffic Control / Hazard Warning | 150 kWe / 580 kWe | 2005 / 2010 | Intermediate | SD / CBC, Stirling |
| ***Propulsion*** | | | | |
| 81 - SEP Vehicle | 50 - 150 kWe | 2004 | LEO - Lunar Orbit | PV / Battery, SD / CBC, Stirling |
| 82 - NEP Vehicle | 5 - 40 MWe | 2016 | TMI & TEI | LMR / K-Rankine |

* Candidates based on Task 1C results (NAS3-24902)

## TABLE 1-2. LUNAR AND MARS MISSION SCENARIO SUMMARY

| PLATFORM / DESCRIPTION | POWER | OPERATIONAL TIME-FRAME | LOCATION | POWER SYSTEMS * |
|---|---|---|---|---|
| ***Lunar Missions*** | | | | |
| 71 - Pressurized rover | 7 (12 Peak) kWe | 2004 | Lunar Surface | DIPS |
| 72 - Payload unloader | 3 (10 Peak) kwe | 2004 | Lunar Surface | RFC |
| 73 - LEV servicer | 10 kWe | 2004 | Lunar Surface | DIPS |
| 74 - Regolith hauler | 3 (15 Peak) kWe | 2008 | Lunar Surface | RFC |
| 75 - Mining excavator | 22 (40 Peak) kWe | 2008 | Lunar Surface | RFC |
| 76 - Initial lunar outpost | 25 kWe | 2004 | Lunar Surface | PV / RFC |
| 33 - Permanent lunar base | 130 kWe / 2081 kWe | 2005 / 2013 | Lunar Surface | LMR / Stirling, CBC, Thermionic |
| 34 - Lunar transport | 1 kWe / 15 kWe | 2000 / 2030 | Lunar Surface | DIPS, PFC, PV / RFC |
| 36 - Field erection/assembly machine | 2.0 kWe | 2005 | Lunar Surface | DIPS, PFC, PV / RFC |
| 37 - Cable laying machine | 1.0 kWe | 2005 | Lunar Surface | DIPS, PFC, PV / RFC |
| 38 - Emergency ascent vehicle | 10.0 kWe | 2005 | Lunar Surface / LEO | DIPS, PFC, PV / RFC |
| 40 - Lunar geoscience orbiter | 0.1 kWe | 2006 | Lunar Polar Orbit | RTG |
| 41 - Seismic monitoring station | 0.1 kWe | 2014 | Lunar Surface | RTG |
| 42 - Space plasma observatory | 33.5 kWe | 2012 | Lunar Surface | PV / RFC, LMR / Stirling, CBC |
| 43 - Comm/support satellite | 55.0 kWe | 2007 | L2 | PV / Battery, SD / CBC, Stirling |
| 44 - Infrared observatory | 10.0 kWe | 2007 | Lunar Surface | DIPS, PFC, PV / RFC |
| 45 - Gamma ray observatory | 10.0 kWe | 2007 | Lunar Surface | DIPS, PFC, PV / RFC |
| 46 - Remote cosmic neutrino detector | 2.0 kWe / 3.0 kWe | 2007 / 2018 | Lunar Surface | DIPS, PFC, PV / RFC |
| 47 - 100-m thinned aperture optical telescope | 25.0 kWe | 2008 | Lunar Surface | PV / RFC, LMR / Stirling, CBC |
| 48 - Radio telescope facility | 10.0 kWe | 2008 | Lunar Surface | DIPS, PV / RFC |
| ***Mars Missions*** | | | | |
| 50 - Mars film mapping mission | 0.1 kWe | 1999 | Mars Orbit | PV / Battery, DIPS, MOD-RTG |
| 51 - Mars rader mapping mission | 0.7 kWe | 2005 | Mars Orbit | PV / Battery, DIPS, MOD-RTG |
| 52 - Mars rover sample return mission | 0.6 kWe | 2007 | Mars Orbit & Surface | PV / Battery, DIPS, MOD-RTG |
| 53 - Mars observer mission | 0.2 kWe | 2010 | Mars Orbit | PV / Battery, DIPS, MOD-RTG |
| 54 - Mars dual network mission | 0.1 kWe | 1999 | Mars Orbit & Surface | PV / Battery, DIPS, MOD-RTG |
| 55 - Mars aeronomy observer | 0.2 kWe | 2007 | Mars Orbit | PV / Battery, DIPS, MOD-RTG |
| 56 - Mars weather monitor #1 | 0.5 kWe | 2007 | Mars Orbit | PV / Battery, DIPS, MOD-RTG |
| 57 - Mars weather monitor #2 | 0.4 kWe | 2008 | Mars Orbit | PV / Battery, DIPS, MOD-RTG |
| 58 - Phobos photo mapping mission | 0.1 kWe | 2001 | Phobos Orbit | PV / Battery, DIPS, MOD-RTG |
| 59 - Phobos sample return mission | 0.8 kWe | 2001 | Phobos Orbit & Surface | PV / Battery, DIPS, MOD-RTG |
| 60 - Permanent weather network | 0.2 kWe | 2008 | Mars Surface | PV / Battery, DIPS, MOD-RTG |
| 61 - Mars communication satellite | 0.7 kWe | 2008 | Mars Synch Orbit | PV / Battery, DIPS, MOD-RTG |
| 62 - Phobos surface base | 35 / 71 / 728 kWe | 2007 | Phobos Surface | LMR / CBC, Thermionic, Stirling |
| 63 - TMI personnel & light cargo vehicles | 25 - 50 kWe | 2006 / 2023 | Trans Mars Ins (TMI) | PV / Battery, LMR / CBC, Stirling |
| 65 - TMI precursor & heavy cargo vehicles | 5 - 10 kWe | 1998 / 2022 | Trans Mars Ins (TMI) | PV / Battery, LMR / CBC, Stirling |
| 66 - Phobos orbiting station | 35 / 303 kWe | 2008 / 2009 | Phobos Orbit | LMR / CBC, Thermionic, Stirling |
| 77 - Pressurized rover | 7 (12 Peak) kWe | 2014 | Mars Surface | DIPS |
| 78 - Payload unloader | 3 (10 Peak) kWe | 2014 | Mars Surface | RFC |
| 79 - MEV servicer | 10 kWe | 2014 | Mars Surface | DIPS |
| 80 - Initial Mars outpost | 25 kWe | 2014 | Mars Surface | PV / RFC |
| 83 - Permanent Mars base | 800 kWe | 2030 | Mars Surface | LMR / Stirling, CBC, Thermionic |

* Candidates based on Task 1C results (NAS3-24902)

The lunar missions (Table 1-2) consist primarily of surface activities with an initial lunar outpost established in 2004 and a permanent lunar base in 2005. Science activities on the lunar surface focus on astronomy and physics with facilities for a gamma ray observatory, an infrared observatory, and a 100-m thinned aperture optical telescope. Mobile platforms, principally defined from 90-day study results, include pressurized and unpressurized rovers, a payload unloader, a mining excavator and a LEV servicer.

The Mars missions in Table 1-2, can be grouped into three areas: precursor/orbital, Phobos (surface and orbital), and Mars surface. The precursor/orbital missions consist of reconnaissance and sample return missions to both Phobos and Mars, and communications and weather satellites in Mars orbit. There is also a Phobos space station and surface base primarily for in-situ resource processing. The Mars surface activities include an initial Mars outpost being established in 2014 with a permanent Mars base in 2030. Mobile platforms for the Martian surface are similar in function and application to those on the lunar base.

## 1.2 TECHNOLOGY REQUIREMENTS

For each of the platforms in the scenario identified in Subtask 1.1, power requirements were identified and power systems and related technologies were selected per the results of SSEP Task 1C. Additional technologies such as In-core Thermionics and Radioisotope Stirling, which were previously not considered, were included where applicable.

Activities in each platform were examined to develop a profile of power needs over the lifetime of the activity. Therefore, temporal power requirements were clearer and power technologies that satisfy these requirements could then be selected. In addition, life requirements and allowable modularity for a technology could also be determined. Results of Task 1C and Rocketdyne engineering expertise were utilized as much as possible to establish top level power system architectures to meet the power needs.

Figures 1-1 through 1-12 illustrate the power profiles, module number and size selection, and power system technology selection for these platforms. The modules are shown as providing initial and supplementary capability as well as replacements for modules whose life has expired. Some platforms were simple enough that a power profile plot was not necessary to illustrate the selection of number of modules and module sizes. The module size is based on the power requirement profile for a given platform, module life and the power system type used to satisfy the power requirements. The size that provides a reasonable fit for the profile with a minimum number of total modules is selected.

All power system data for each platform were integrated into matrices shown in Figures 1-13 and 1-14. These figures represent the mission scenario and power technologies applicable at each power level and timeframe. The figures are useful in visualizing how a particular technology is applied over a number of different missions with different power levels spanning different timeframes.

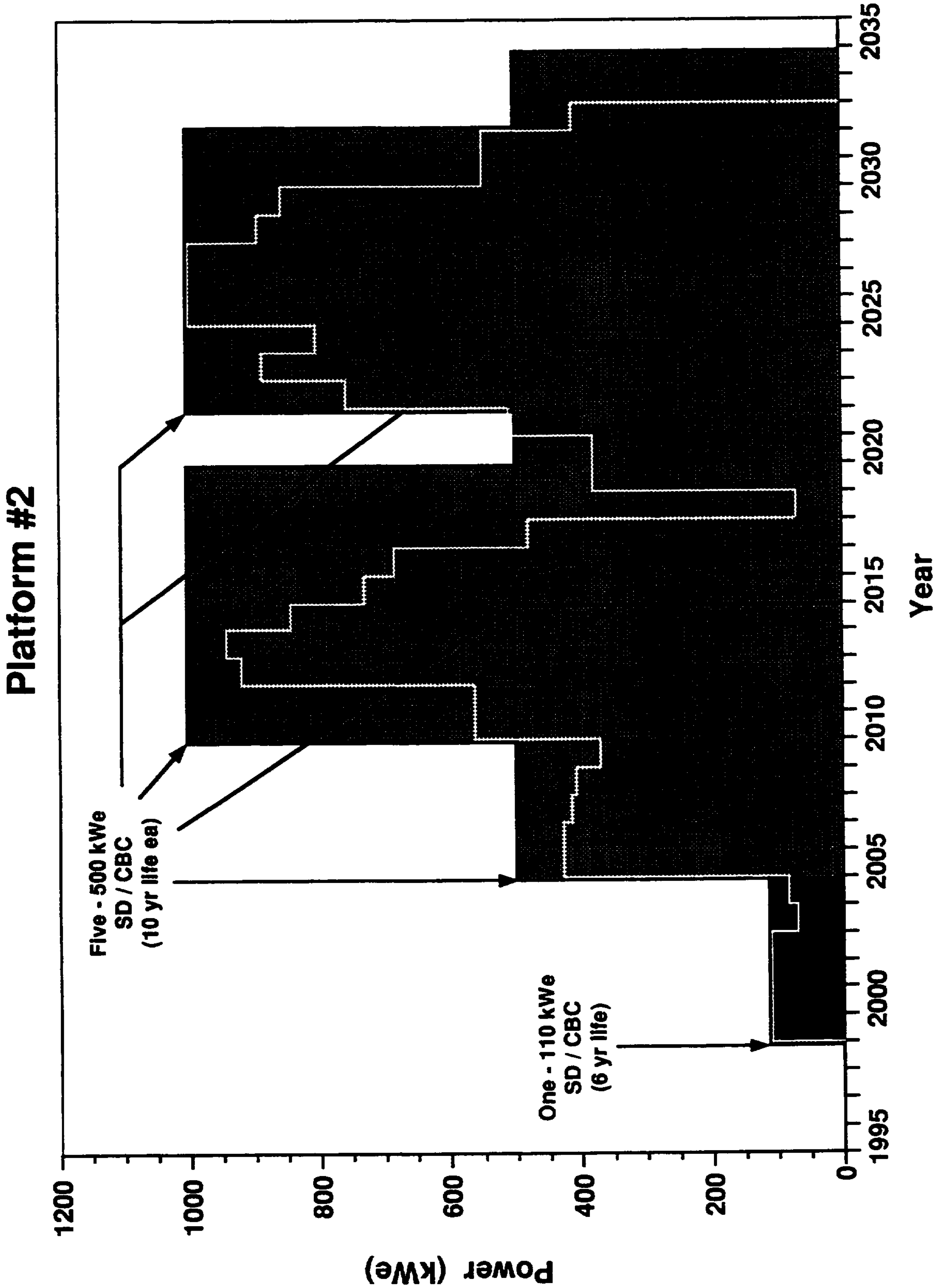


Figure 1-1 Size and Number of Modules for Platform 2 Power System

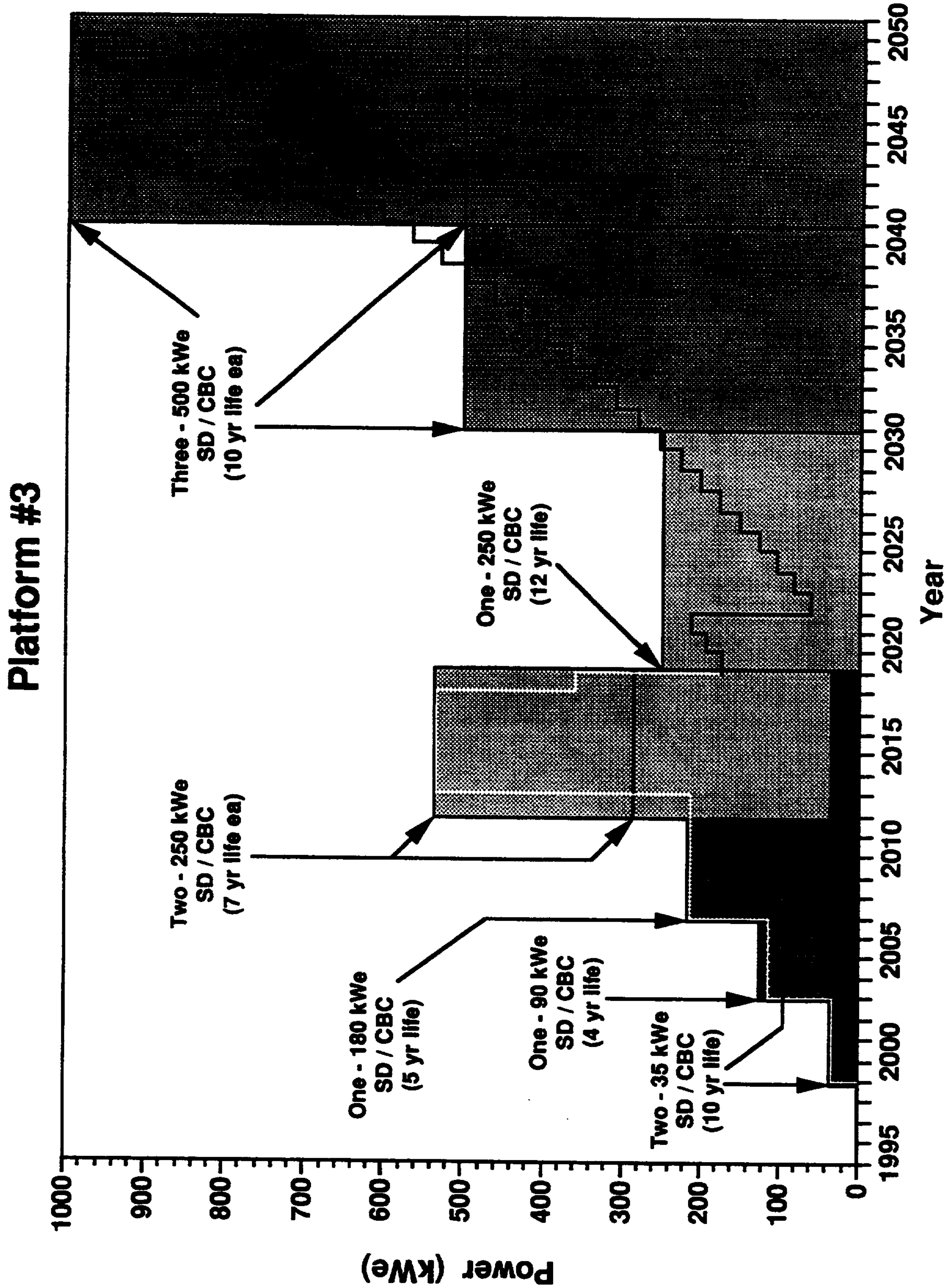


Figure 1-2. Size and Number of Modules for Platform 3 Power System

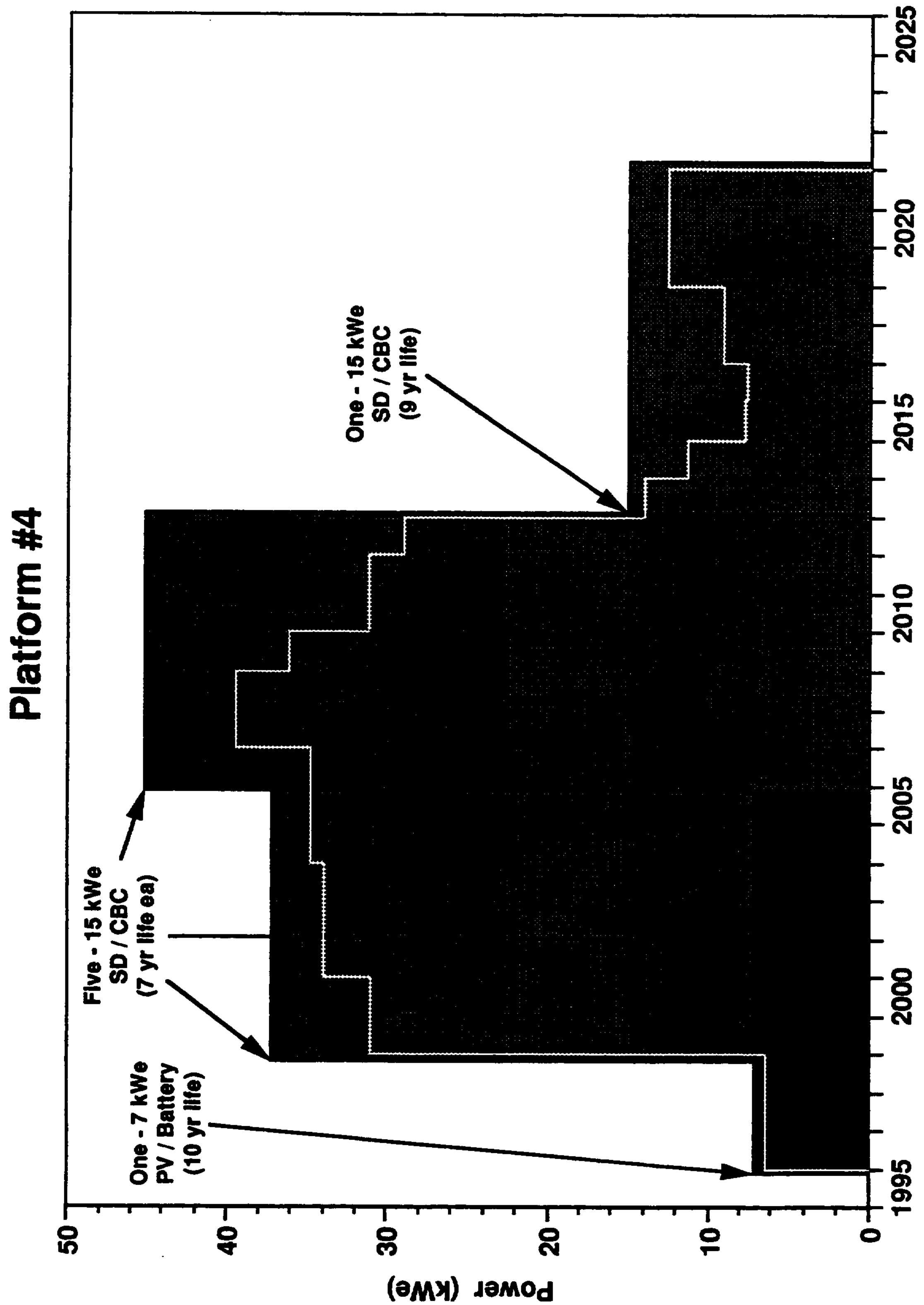


Figure 1-3. Size and Number of Modules for Platform 4 Power System

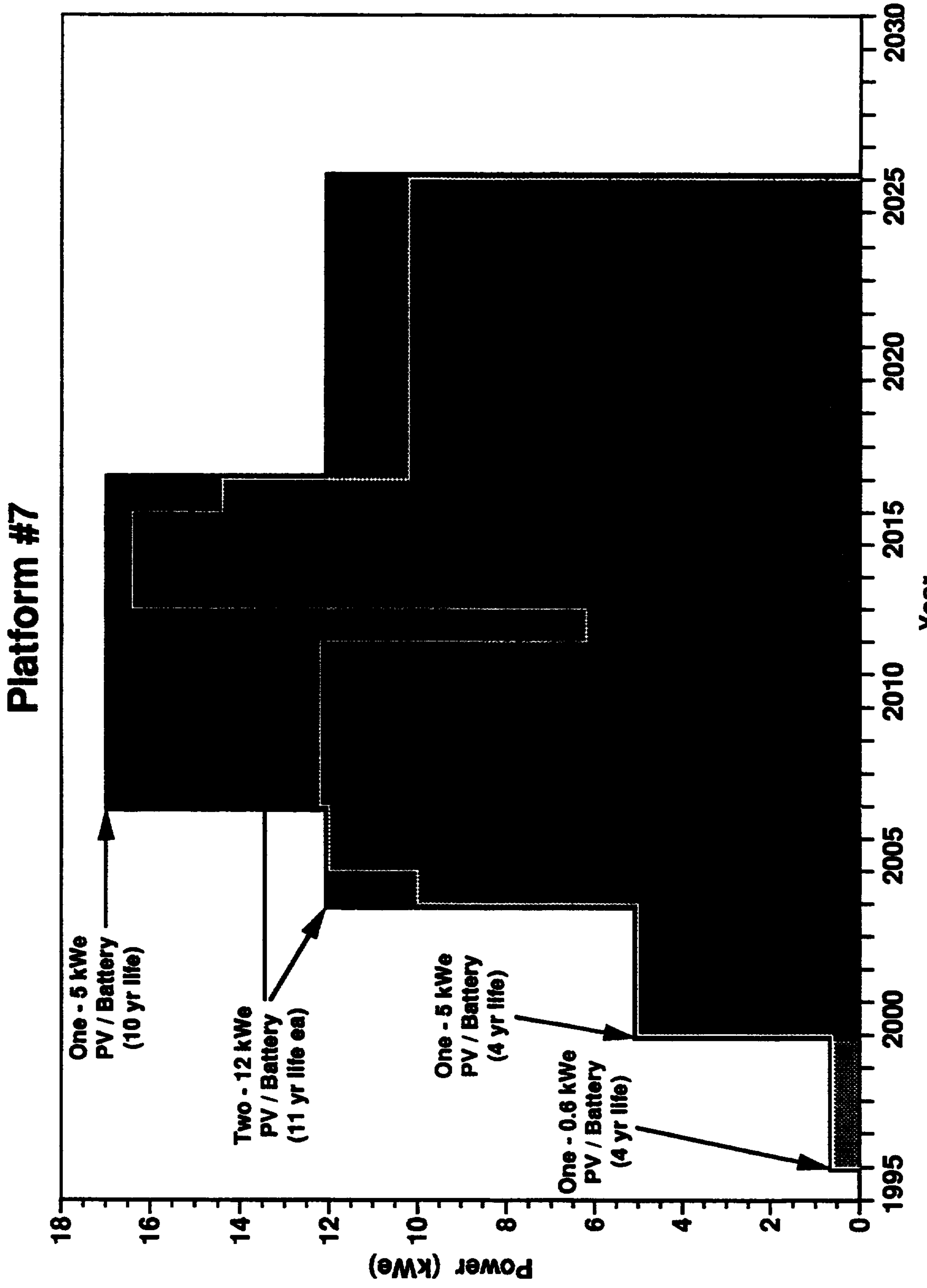


Figure 1-4. Size and Number of Modules for Platform 7 Power System

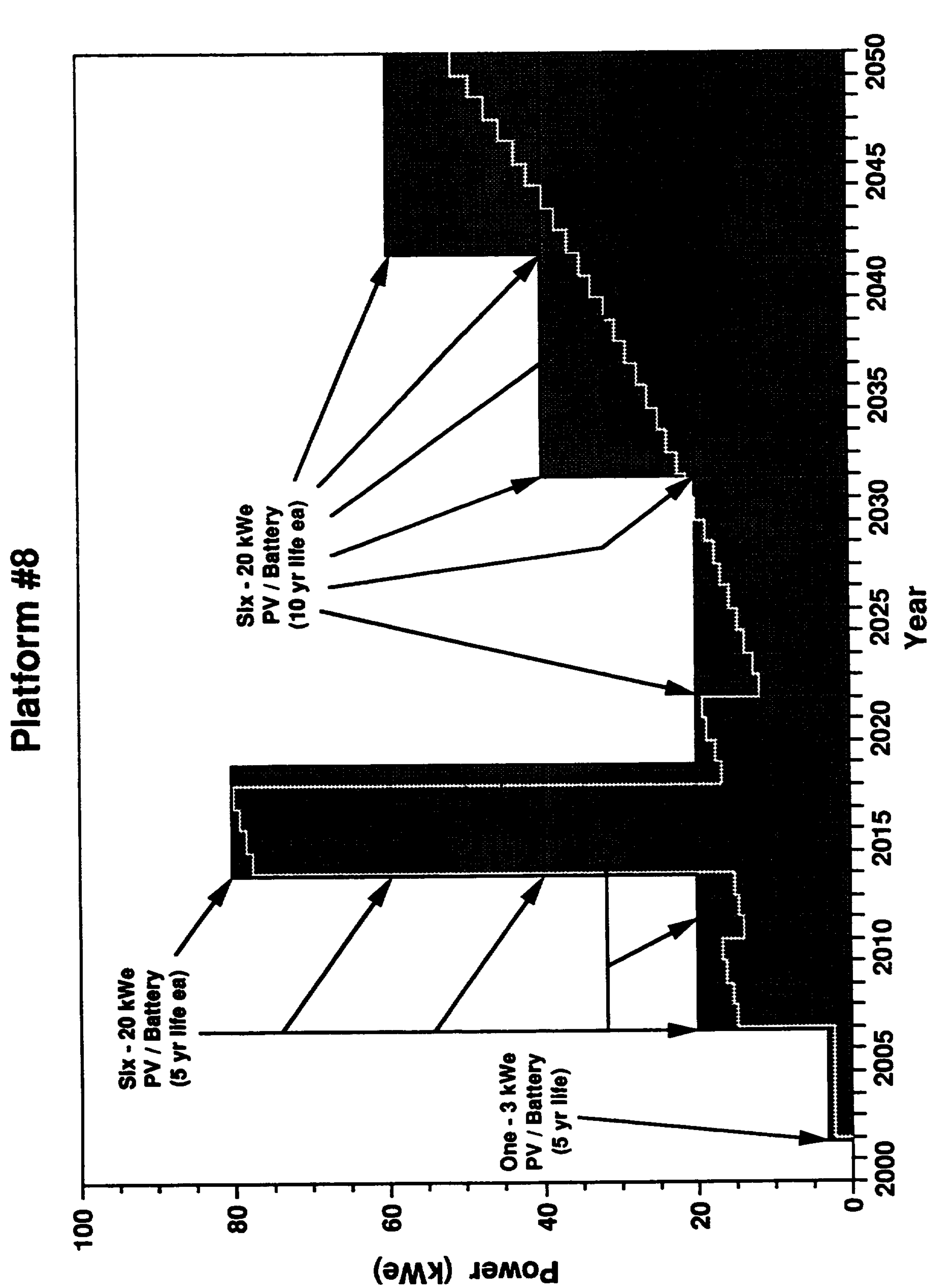


Figure 1-5. Size and Number of Modules for Platform 8 Power System

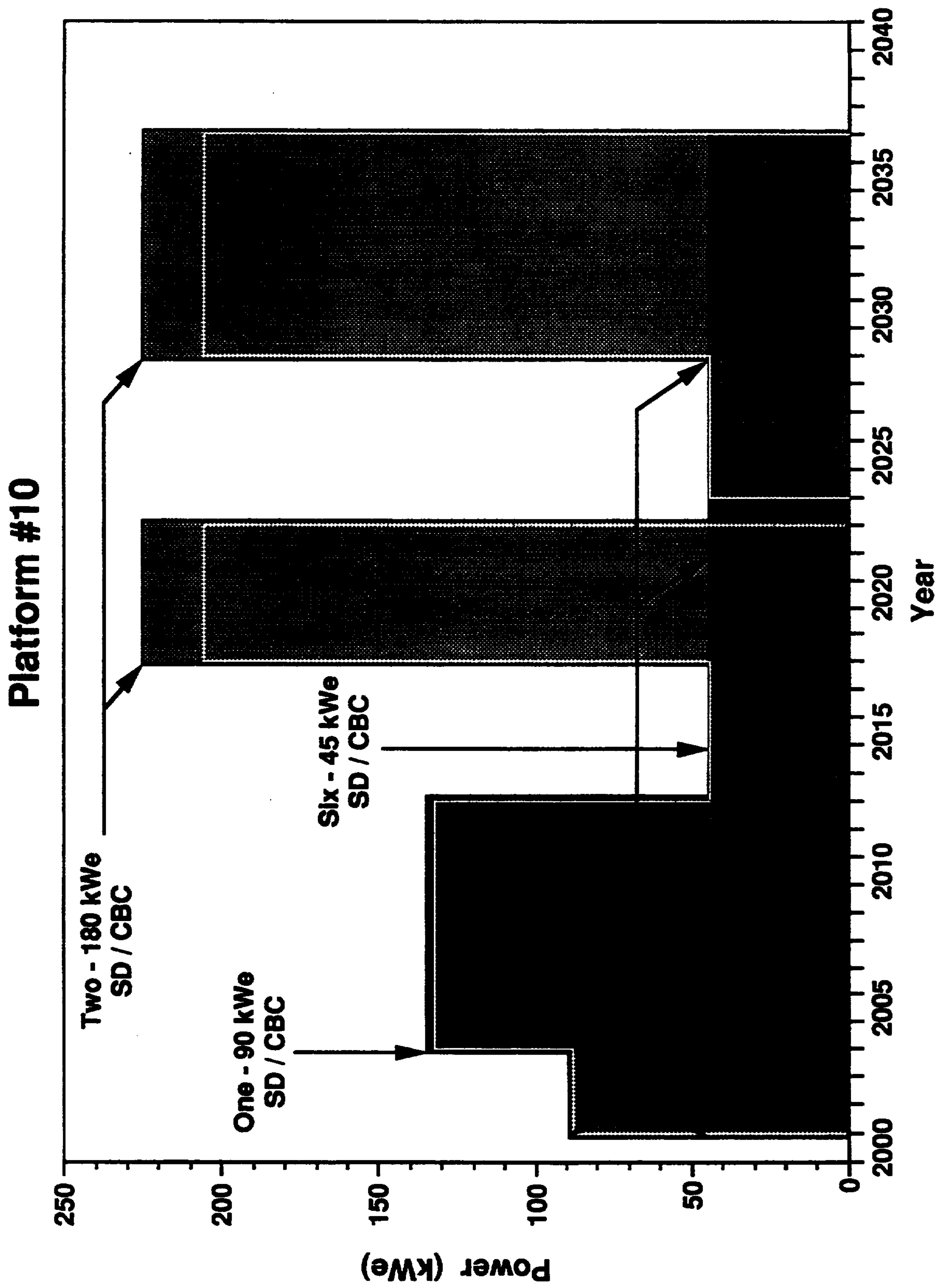


Figure 1-6. Size and Number of Modules for Platform 10 Power System

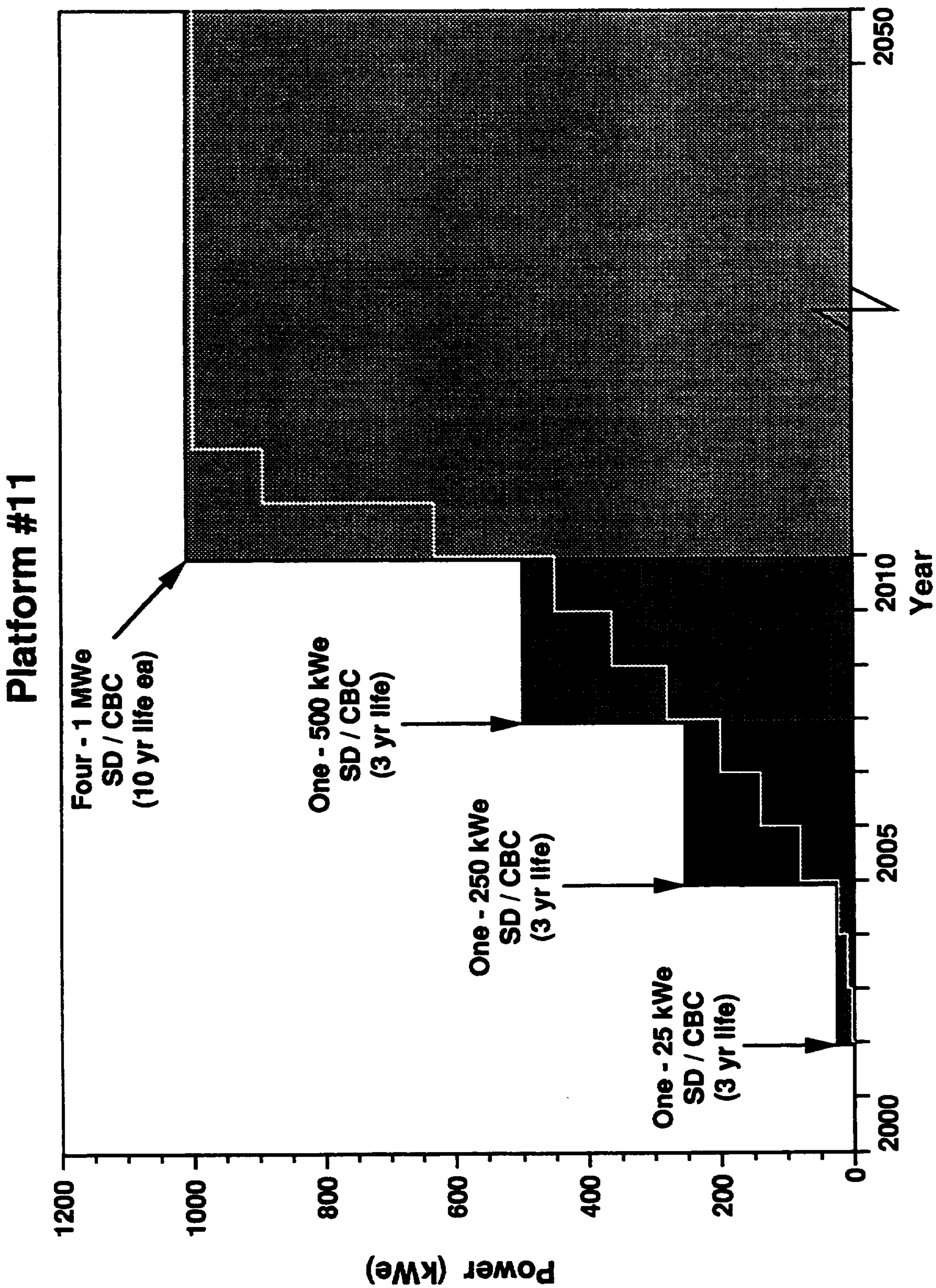


Figure 1-7. Size and Number of Modules for Platform 11 Power System

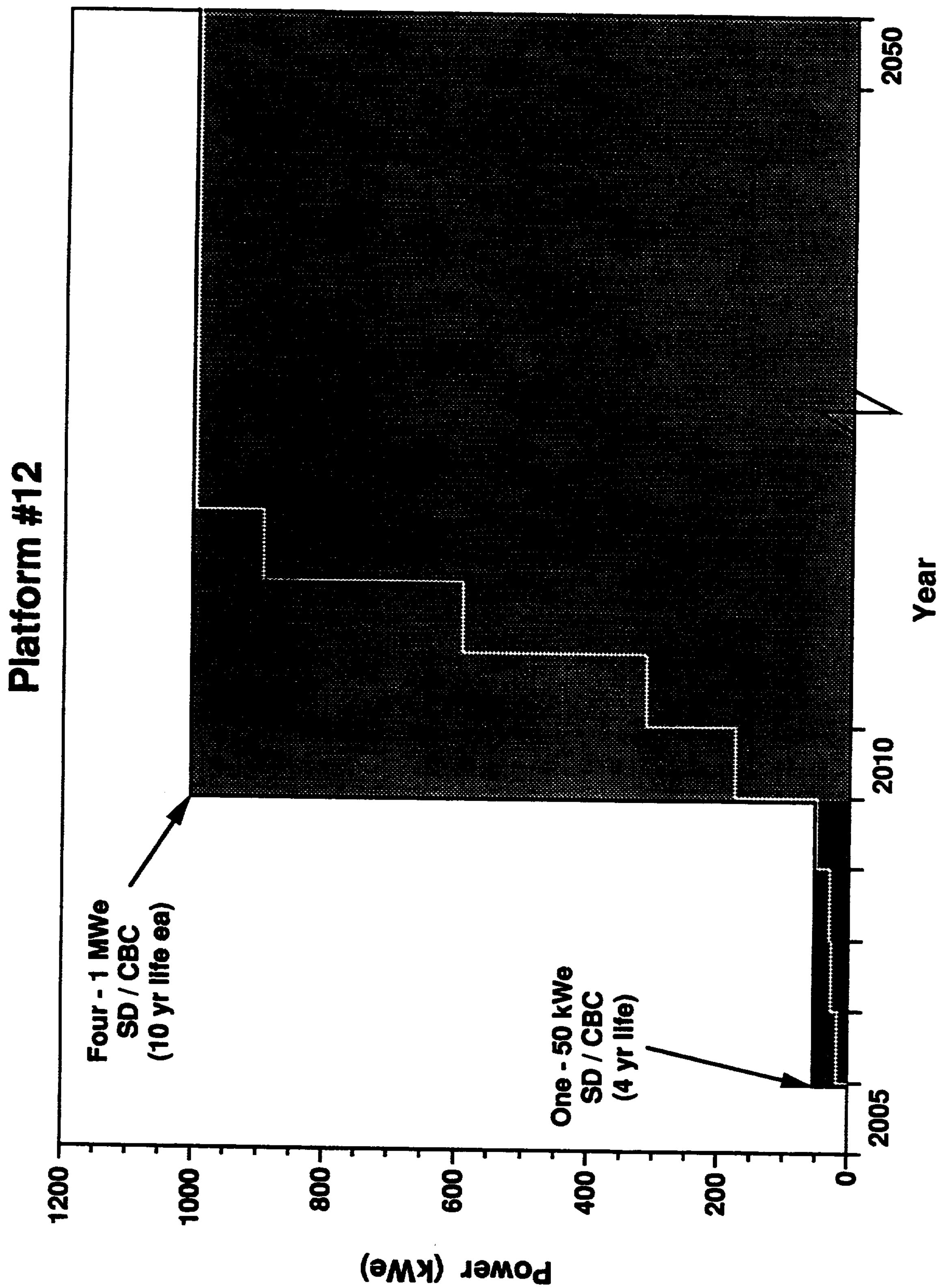


Figure 1-8. Size and Number of Modules for Platform 12 Power System

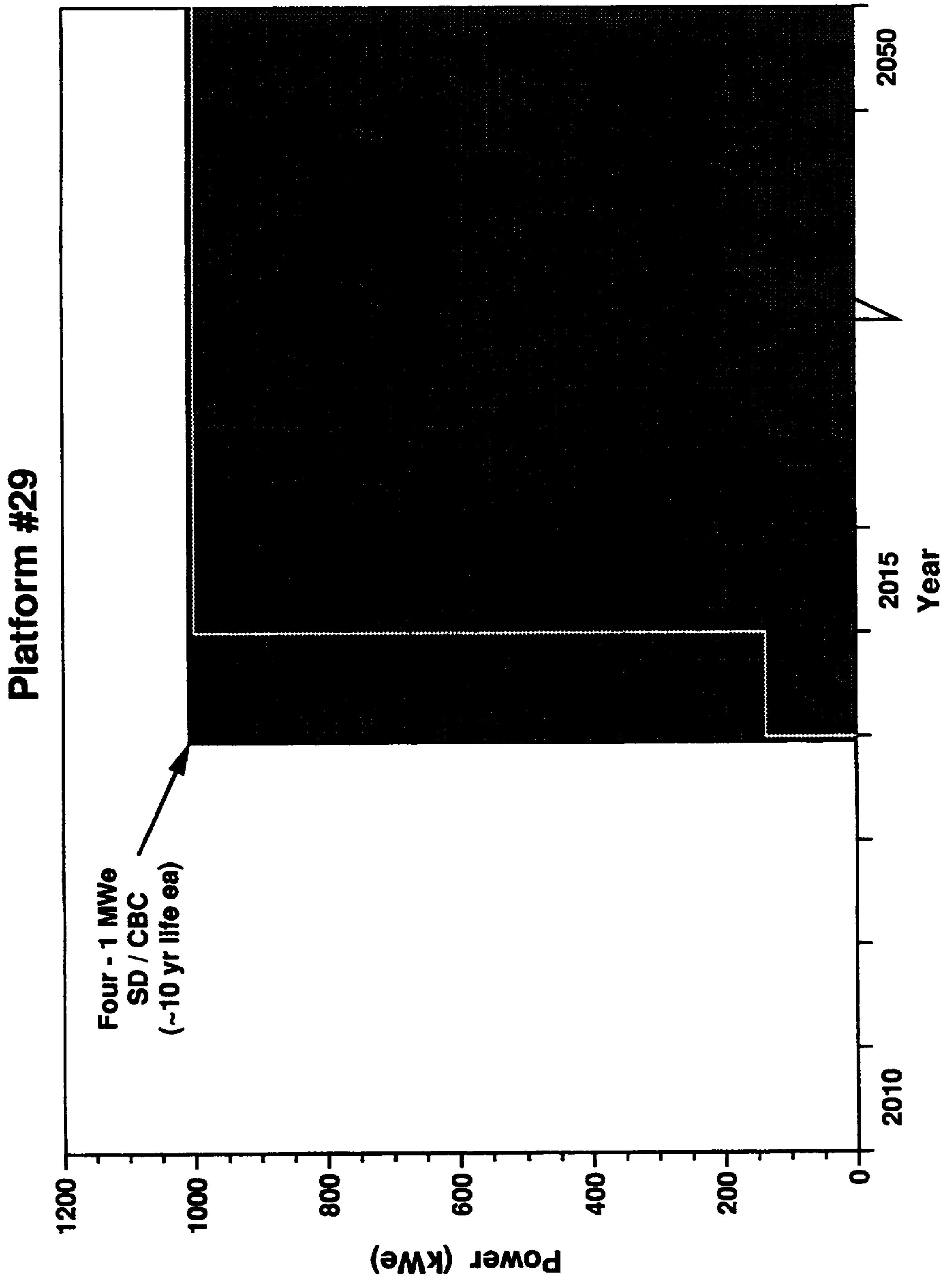


Figure 1-9. Size and Number of Modules for Platform 29 Power System

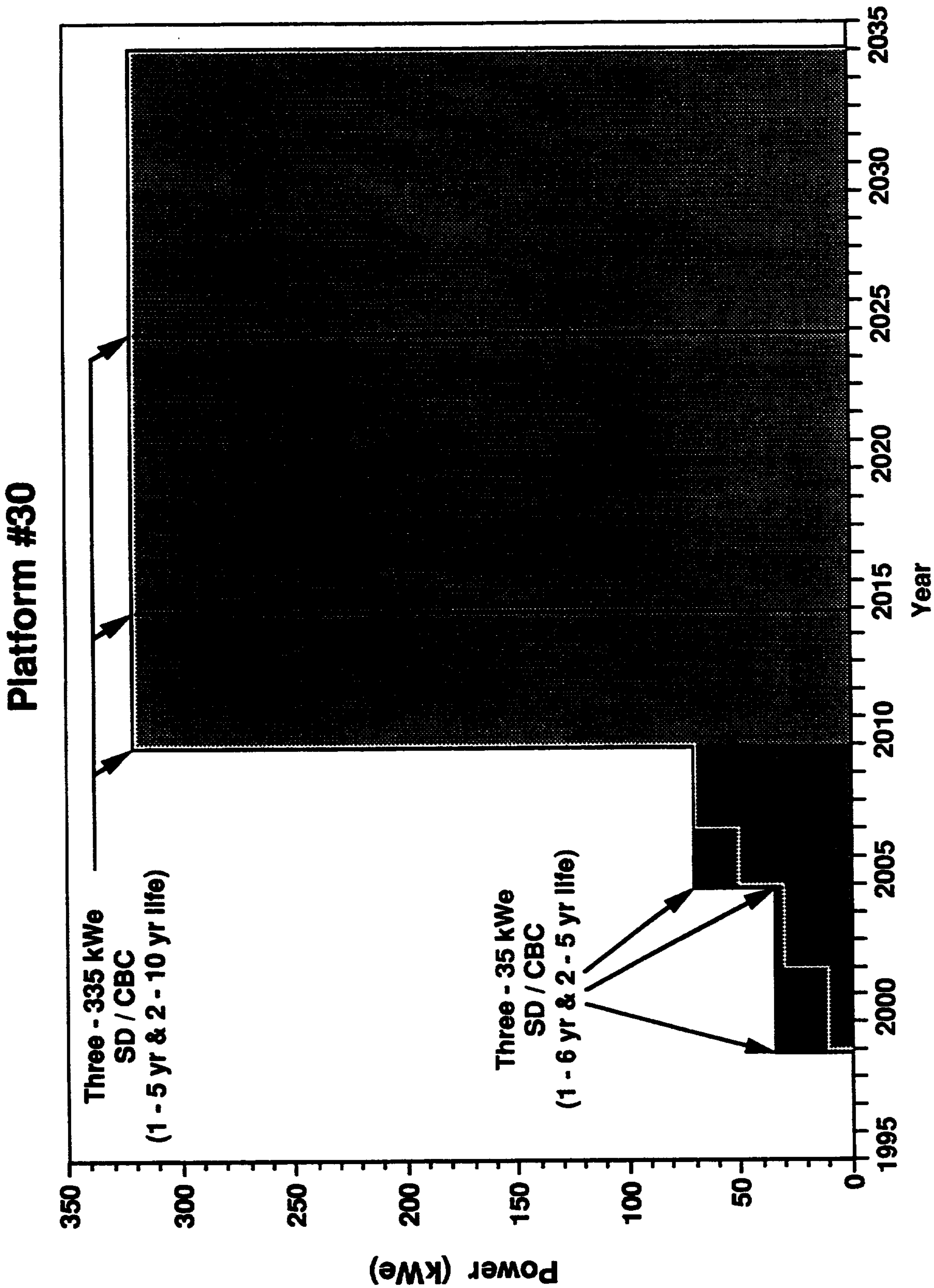


Figure 1-10. Size and Number of Modules for Platform 30 Power System

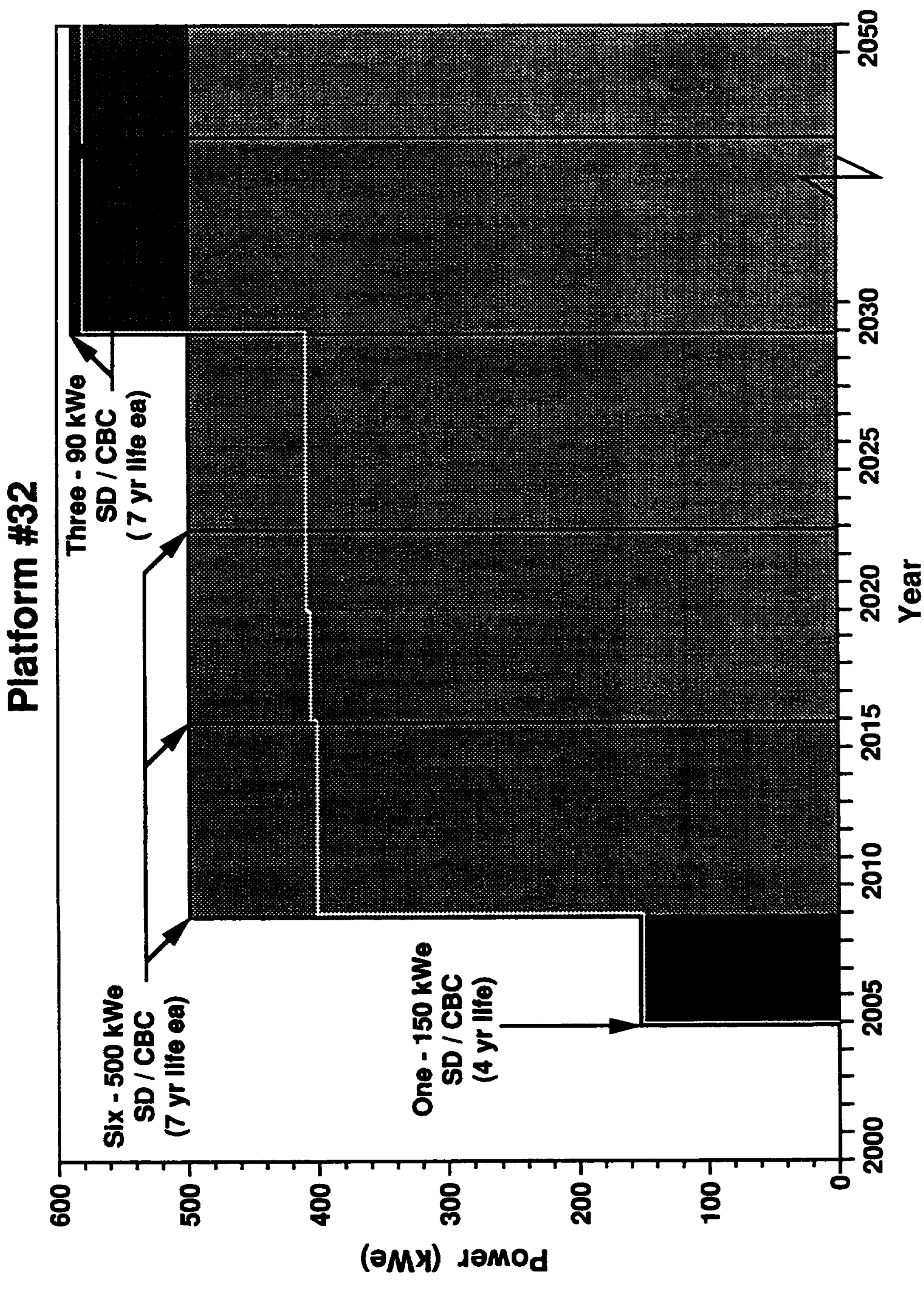


Figure 1-11. Size and Number of Modules for Platform 32 Power System

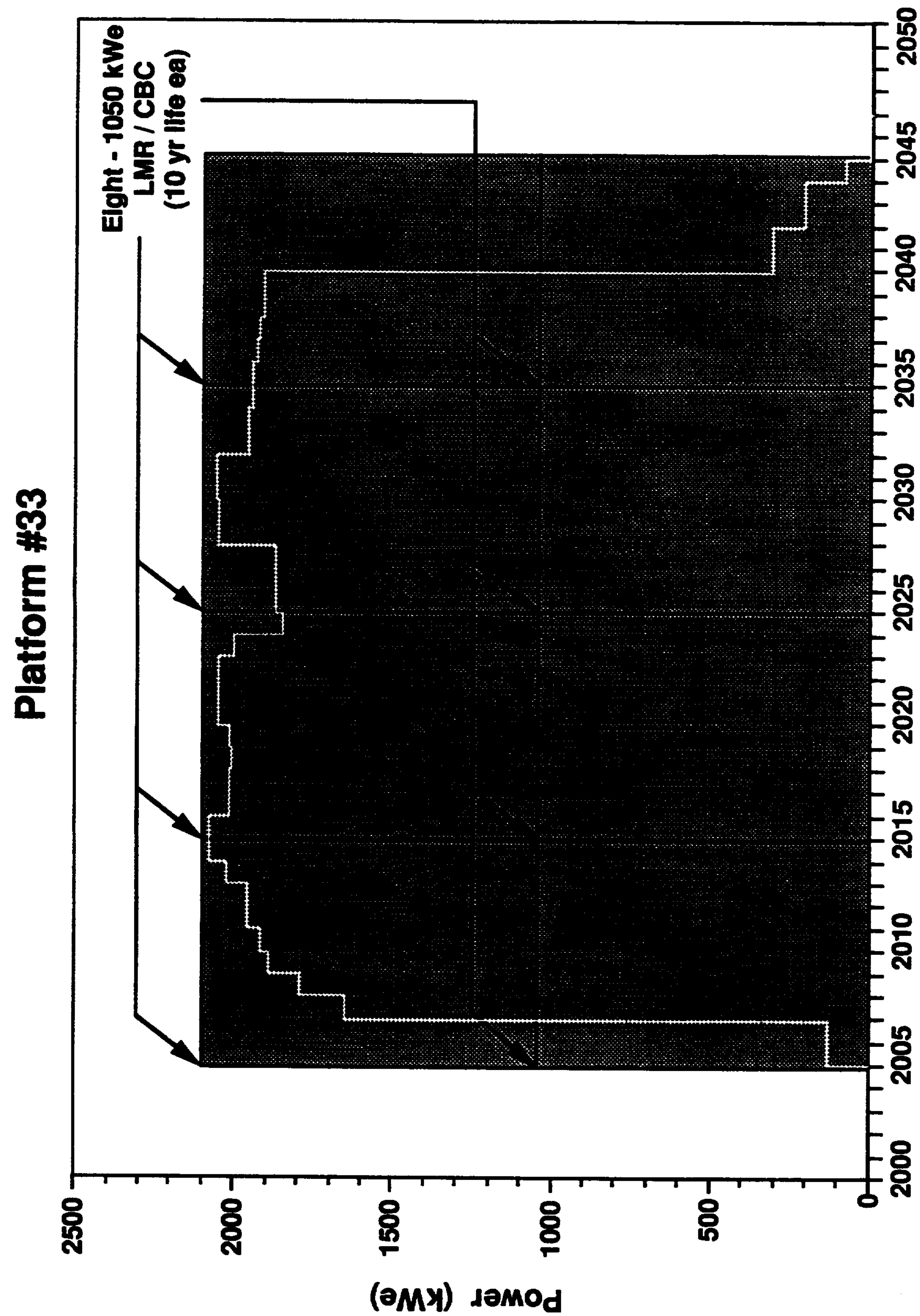


Figure 1-12. Size and Number of Modules for Platform 33 Power System

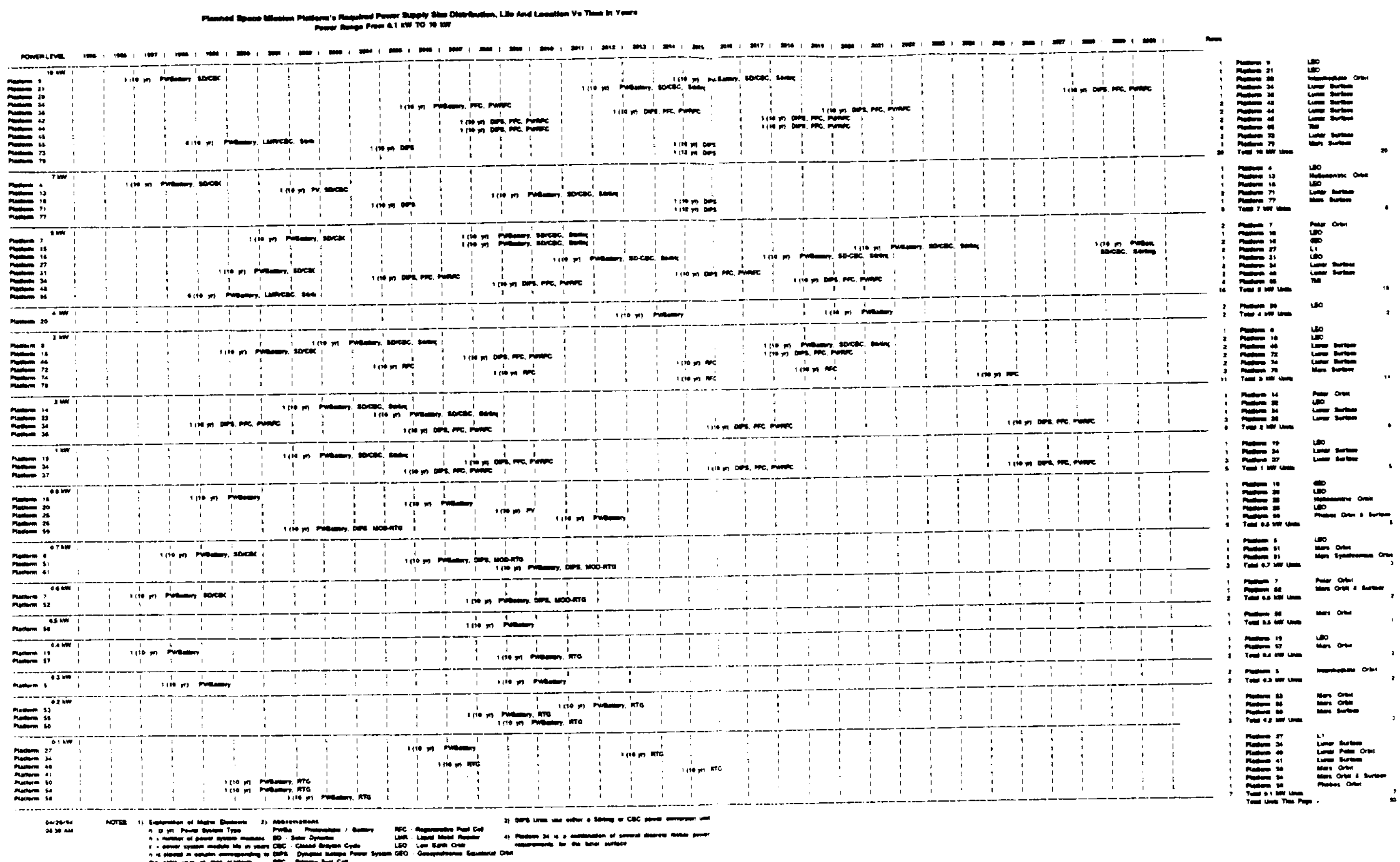


Figure 1-13. Power System Applicability Matrix for Low Power Missions



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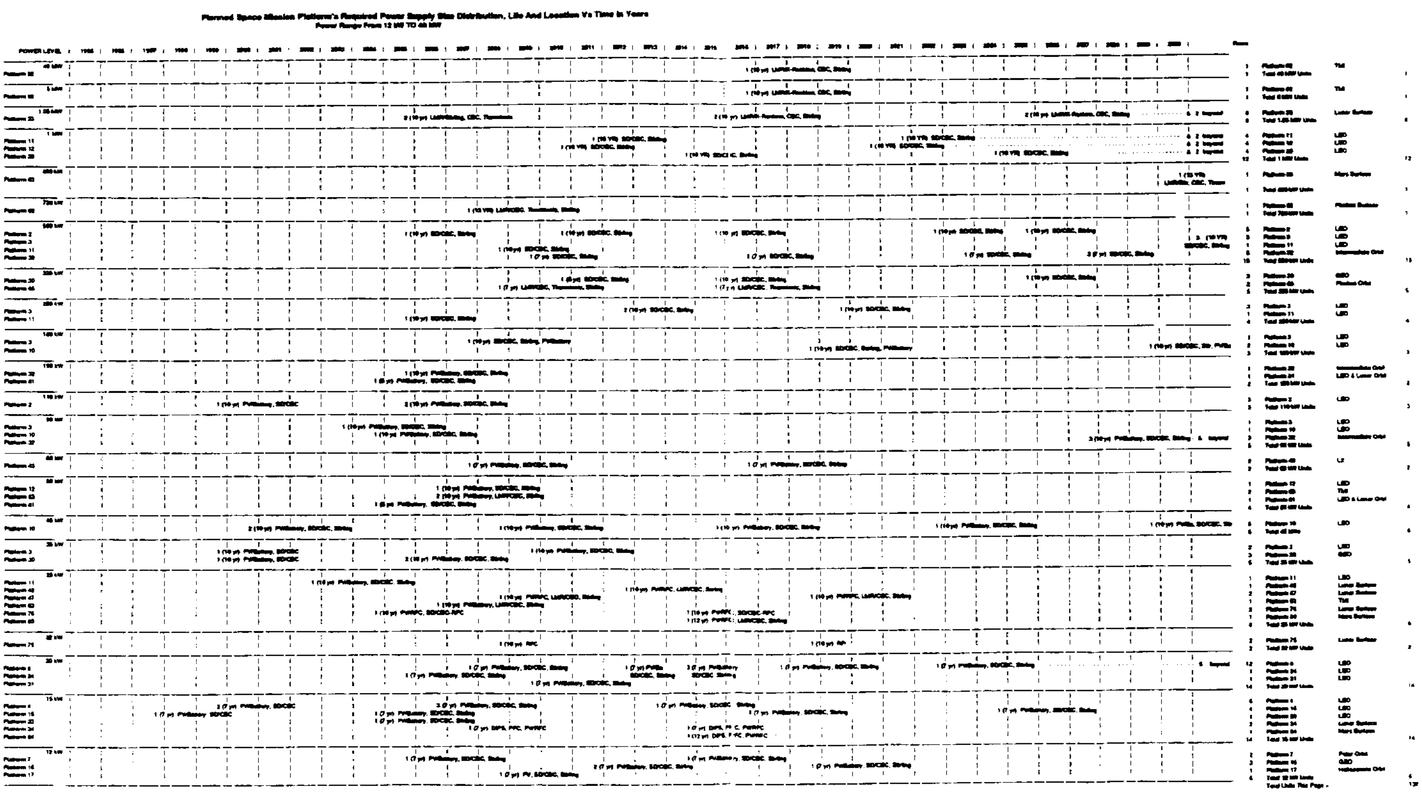



Figure 1-14. Power System Applicability Matrix for High Power Missions

## 1.3 LIFE CYCLE COST (LCC) ANALYSIS

A methodology to assess the technology benefits of different power system technologies based on their LCCs was formulated. The proposed methodology, shown in Figure 1-15, determines LCC of the power technologies for the selected set of missions. The set includes the number of platforms required, mission location and life. These data are used in combination with necessary technology development timeframe when the technology is needed. Power system parameters include module power level, energy storage requirements, module life and the total number of modules required to meet the mission power requirement. The module parameters based on technology level are then used in characterizing the module in terms of maximum operating temperature, cycle efficiency, specific mass and drag area (for LEO missions). Finally, the power system technical characteristics are used to determine module mass and module LCC.

The power system technologies are selected from several competing for different mission categories in a given timeframe based on the LCC. Nominal technology growth plans are considered to project development in this timeframe for the those technologies. Relative development cost impacts are estimated, assuming a nominal, progressive development investment path and technology cost inheritance factors. The technical improvements and associated costs are then incorporated for successive generations of power systems. The technology parameters for typical power system technologies are shown in Tables 1-3, 1-4 and 1-5.

The applicability of power systems for all qualifying missions is defined and the appropriate number of power system modules are determined for each platform, since this impacts module development and production costs (Table 1-6).

Parameters such as system life, maximum operating temperature, cycle efficiency, system mass, areas and power levels have a bearing on replacement costs (e.g., for LMRs) and on reboost costs (for platforms in LEO).

The total power system LCC is defined as the sum of costs for the following five elements: DDT&E, production (flight units), transportation to mission location, replacement and reboost .

A spreadsheet was developed to calculate the LCCs based on the input characteristics of a technology, cost estimation relationships (CERs) developed for different technologies and operational and maintenance characteristics. Typical strategies for implementation, the approach to calculate LCC for a particular strategy, typical groundrules and assumptions, and the CERs are presented in the following sections. The spreadsheet format and details are discussed in section 1.4.

Based on this methodology, the LCCs for a given set of missions can be compared both on the basis of different power system technologies and different timeframes (e.g. mid-term and far-term), as shown in Figure 1-16.

Due to time and resource limitations, a complete LCC analysis was performed for only one technology, namely the dynamic isotope power system (DIPS) with closed Brayton cycle (CBC) conversion. A set of missions with power requirements varying from 0.5 kWe to 15 kWe was selected and these power systems were characterized for the near-term, mid-term, and far-term timeframes. Finally, LCCs of the DIPS units were estimated and compared for different technology implementation strategies reflecting one-time technology development versus on-going development over a 35 year period covering the foreseeable NT, MT and FT timeframes. Benefits of on-going development efforts were included in the LCC calculations. The results are presented and discussed in section 1.5.

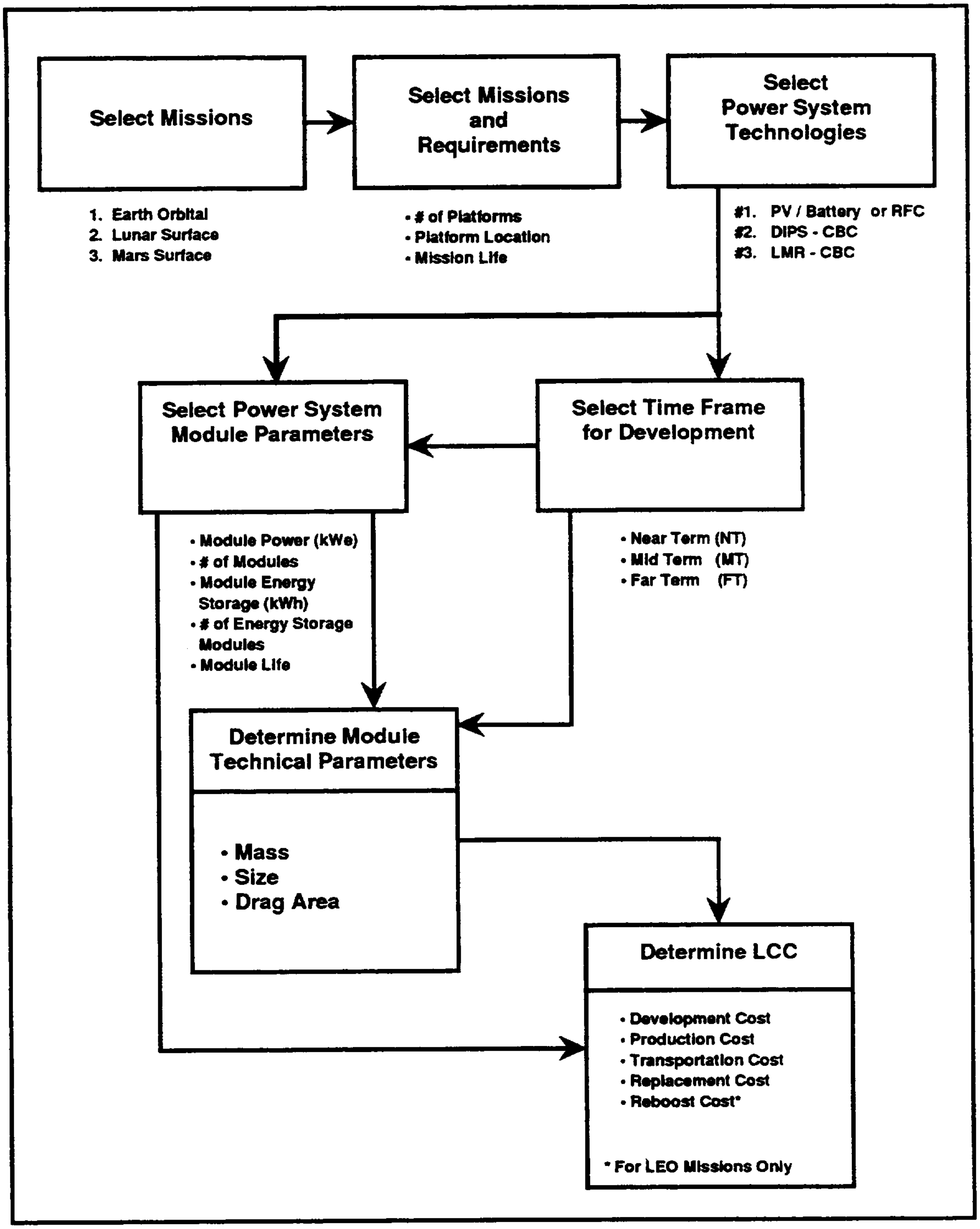



Figure 1-15. Technology Benefit Assessment Based on LCC

TABLE 1-3. PHOTOVOLTAIC TECHNOLOGY PARAMETERS

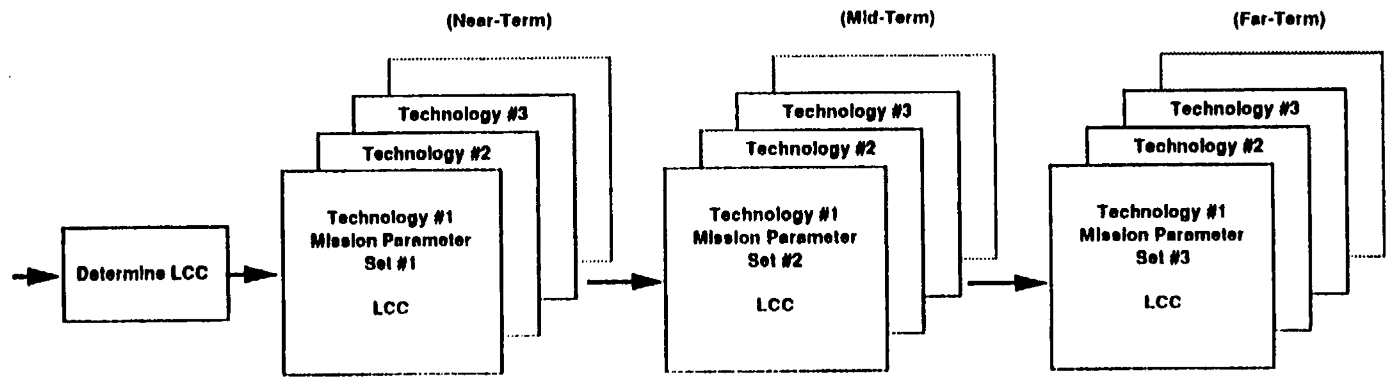
| Component/Timeframe | Near-Term | Mid-Term | Far-Term |
|---|---|---|---|
| | | | |
| ***PV Array*** | | | |
| Cell Type | GaAs/Ge (inactive) | AlGaAs/Ge (active) | Conc. GaAs/GaSb |
| Watts/m^2 | 135 | 180 | 255 |
| Life (years) | 15 | 15 | 15 |
| Cell Efficiency (%) | 18 | 21 | 30 |
| | | | |
| ***Energy Storage*** | | | |
| **Battery** | NiH2 | NaS | NaS |
| Specific Energy (W-hr/kg) | 50 | 70 | 110 |
| Life (years) | 5 | 5 | 7 |
| **Regenerative Fuel Cell** | High pressure gas | High pressure gas | Cryo |
| Specific Energy (W-hr/kg) | 50/500* | 100/700 | 150/1000 |
| Life (years) | 2 | 5 | 7 |
| | | | |
| ***PMAD*** | | | |
| Efficiency (%) | 90 | 92 | 94 |
| | | | |
| ***Total Power System (with PMAD but without energy storage)*** | | | |
| Specific Mass (kg/kWe) (with PMAD) | 40 | 32 | 25 |

* Long Duration Storage

TABLE 1-4. DIPS TECHNOLOGY PARAMETERS

| Component/Timeframe | Near-Term | Mid-Term | Far-Term |
|---|---|---|---|
| | | | |
| ***Power Conversion*** | | | |
| Converter Hot Side Temperature (K) | 1133 | 1300 | 1450 |
| Life (years) | 15 | 15 | 15 |
| | | | |
| ***Heat Rejection*** | | | |
| Specific HEX Area (m^2/kWe) | 7 | 5 | 4 |
| | | | |
| **Total Power System** | | | |
| Specific Mass (kg/kWe) | 167 | 167 | 137 |
| Cycle Efficiency (%) | 22 | 26 | 27 |

Basis: 5 kWe




**Key Technology Benefit Assessment Comparisons**

- LCC of Technology #1 vs. LCC of Technology #2 and #3 at constant mission parameter sets and constant technology level
- LCC of Technology Level #1, #2, #3 vs. Those at upgraded Technology Levels

**Trades / Sensitivities**

- LCC vs. Mission Parameter Sets
- LCC vs. Power Module Parameters
- LCC vs.Cost assumptions

Figure 1-16. Output of Technology Assessment Model

## TABLE 1-5. LIQUID METAL REACTOR TECHNOLOGY PARAMETERS

| Component/Timeframe | Near-Term | Mid-Term | Far-Term |
|---|---|---|---|
| | | | |
| ***Power Generation*** | | | |
| Turbine Inlet Temperature (K) | 1140 | 1360 | 1450 |
| Life (years) | 10 | 10 | 10 |
| | | | |
| ***Heat Rejection*** | | | |
| Heat Pipe Material | 347 SS+ Lock Alloy | C/C+Ni | C/C+Ni |
| Fluid | Hg | Hg | Hg |
| | | | |
| **Total Power System** | | | |
| Specific Mass (kg/kWe)* (Inc. Shield) | 81 | 38 | 30 |
| Cycle Efficiency (%) | 18.5 | 20.4 | 22.5 |

* Shield Mass ≈ 50% of Power System

## TABLE 1-6. ESTIMATED NUMBER OF POWER MODULES (NM) USED FOR LCC

| Max. User Power Level kWe | PV | | DIPS/CBC | | LMR/CBC | |
|---|---|---|---|---|---|---|
| | Nm | kWe/Module | Nm | kWe/Module | Nm | kWe/Module |
| | | | | | | |
| 0.5 | CERs Not Applicable* | | 1 | 0.5 | Not Attractive | |
| 1.0 | " " | | 1 | 2.5 | " " | |
| 2.5 | " " | | 1 | 2.5 | " " | |
| 5.0 | 1 | 5 | 2 | 2.5 | " " | |
| 10.0 | 2 | 5 | 4 | 2.5 | " " | |
| 15.0 | 3 | 5 | 6 | 2.5 | " " | |
| 20.0 | 4 | 5 | Not Attractive | | " " | |
| 25 | 5 | 5 | " " | | CERs Not Applicable* | |
| 50 | 2 | 25 | " " | | " " | |
| 100 | 4 | 25 | " " | | 3 | 50 |
| 200 | 4 | 50 | " " | | 3 | 100 |
| 250 | Not Attractive | | " " | | 3 | 125 |
| 500 | " " | | " " | | 5 | 125 |
| 750 | " " | | " " | | 4 | 250 |
| 1000 | " " | | " " | | 5 | 250 |
| 5000 | " " | | " " | | 6 | 1000 |
| 40000 | " " | | " " | | CERs Not Applicable* | |

* Power Level outside the range of CER fidelity

Note: The number of power modules for LMR/CBC include one standby module for redundancy. For example, a 100 KW total power level requires two active 50 KW modules and one 50 KW standby module.

### 1.3.1 Methodology for Comparative LCC Analysis of Power Technologies Capturing Many Missions

Some strategies which can be used in comparing power system technologies based on LCC are:

- Limit Development Cost

    - Limited improvement in technologies
    - Penalty: High transportation costs in later years due to high mass
    - Benefit: Low up-front development costs

- Minimize Mass

    - Develop new or improve power technologies to meet near-, mid- and far-term capabilities
    - Penalty: High development costs spread over the years
    - Benefit: Low transportation and replacement costs

- Combination of the above two strategies to minimize the LCC.

    - Limited development
    - Penalty: Development cost
    - Benefit: Low LCC

#### 1.3.1.1 Approach.

- Determine space power system requirements (power level, mission life, calendar year of mission start, platform location in space) for future missions.
- Segment time horizon into near, mid and far term for each technology.
- Identify viable technology options for missions in each time period
- Establish technology upgrading cost factors
- Determine power system life cycle costs (LCC) for the set of missions for each applicable technology and its time of arrival
- Determine overall LCC as function of different technology implementation strategies.

LCC trades can be performed in support of different strategies to test the sensitivity of each strategy to technology parameters and the technical and cost assumptions.

1.3.1.2 Groundrules and Assumptions. The following groundrules and assumptions were used in the analysis:

- All costs in constant FY 1992$

| | | |
|---|---|---|
| • Transportation costs: | LEO | $5.0 K/kg |
| | GEO | $20 K/kg |
| | Moon | $100 K/kg |
| | Mars | $200 K/kg |

- Power Systems
  1. PV/Battery or PV/RFC
  2. DIPS/CBC
  3. LMR/CBC

- Results for CBC also approximately applicable for Stirling: Stirling production costs and replacement costs are similar to those of the CBC.
- Other spacecraft systems cost independent of power technology

1.3.1.3 Cost Algorithm Summary. The generic form of the five LCC categories is as follows:

| | | | |
|---|---|---|---|
| Development Cost : | $C_D$ | = | f(kWe / Module, kWh / Module, # of Module Sizes, Development Repeat Factor) |
| Production Cost : | $C_p$ | = | f(kWe / Module x # of Modules, kWh / Module x # of Modules) |
| Transportation Cost : | $C_T$ | = | ($K / kg)$_{\text{Mission Location}}$ x Mass / Module x # of Modules |
| Replacement Cost : | $C_R$ | = | (Mission Life / Module Life) x ($C_T$ + $C_p$); rounded off to the next higher integer. |
| Reboost Cost* : | $C_B$ | = | f(Module Area,Module Mass,# of Modules,life of mission) |

*for LEO Missions Only

All Cost Estimating Relationships (CERs) above are given for manned missions. Development and Production costs are to be multiplied by 0.5 for unmanned missions.

Development costs are determined at the smallest module size (kWe) at a given timeframe. Production costs are determined at the selected module kWe level for the power system.

In the following, the power system LCC algorithms (excluding development costs) are listed with a rationale for the algorithm factors. The detailed subsystem CERs are shown in later subsections of this document.

- Production Cost (Flight Hardware)

  "Subsystem" below refers to the power system subsystems

$$Cpp = 1.5 * \sum_{i\ \text{Subsystems}} Cpi + D*Z$$

| | | |
|---|---|---|
| $C_{pp}$ | = | Total flight hardware cost of one space power system, M$ |
| $C_{pi}$ | = | Subsystem i flight hardware cost, M$ |
| | | (The subsystem may contain several units, such as $N_B$ batteries) |
| D | = | Plutonium cost factor |
| | = | 8.5 x($KW_e/\eta_c$) for DIPS only ($^{238}Pu$ cost), M$ |
| D | = | 0 for all other power systems |
| Z | = | Factor to account for cheaper foreign sources of Pu (e.g. Russia) |
| | = | 0.75 for foreign Pu 1.0 for domestic Pu |
| $\eta_c$ | = | Cycle Efficiency |

The factor of 1.5 is a systems wrap factor which includes integrating contractor general and administrative (G&A) expenses, management, acceptance testing and system hardware integration, assembly and checkout.

- Transportation Cost

$$C_T = 10^{-3}(K\$/kg)\,[M_1 + M_2];$$

| | | |
|---|---|---|
| $C_T$ | = | Cost of flight hardware transportation to space location M$ |
| $M_1$ | = | System mass w/o energy storage,kg |

$M_2$ = Energy storage subsystem mass, kg

- Replacement Cost

$$C_R = \sum_{\substack{i=1 \\ \text{i subsystems} \\ \text{to be replaced}}}^{n} [(C_{pi} + C_{Ti}) (L_p/L_{si} - 1)]$$

$C_R$ = Replacement cost, M$

$L_P$ = Platform mission life, yrs

$L_{si}$ = Subsystem life, yrs

$C_{Ti}$ = Cost of subsystem transportation to space location, M$

Replacement required if module life is less than mission life

- Reboost Cost (for LEO only)

$$C_B = 1.3 \times 10^{-3} \text{ (K\$/kg) } L_p \text{ } (6.61 \times 0.0625 \text{ A} + 0.00133 \text{ A}^2);$$

$C_B$ = Reboost cost, M$

A = Power System drag area, $m^2$

The reboost cost is based on the average required propellant mass to keep a 10 to 100-ton spacecraft at 500 km LEO altitude within an 11-year solar cycle using a propulsion system with specific impulse of 300 $lb_f$-sec/$lb_m$.

1.3.1.4 Generic Power System Development Cost.

$$C_{DP} = 1.5 \left[ \underset{\substack{\text{Subsystem} \\ \text{Engineering \& Test}}}{\sum_{i=1}^{n} C_{Di}} + 1.0\,E \underset{\substack{\text{Subsystem} \\ \text{Hardware}}}{\sum_{i=1}^{n} C_{Pi}} \right] + DC_{DP}(N_P - 1)$$

$C_{Dp}$ = Total space power system development cost, M$

$C_{Di}$ = Development cost of subsystem i, M$

$N_P$ = Number of power module classes with different power levels

E = Factor to account for residual value of 1 development hardware unit of each subsystem, assumed as 0.5 (generic) (2.5 units were used for subsystem development)

$C_{Pi}$ = Production cost of subsystem i

$DC_{DP}$ = Delta space power system development cost at the system level, $5M for DIPS and PV, $50M for LMR.

It accounts for going from low power level to higher power levels at the same technology level. This is based on the groundrule that higher power levels are just scaleups of low power level modules and technology was developed at the lowest power level within a given architecture and timeframe.

For example, a DIPS architecture has three power systems of 0.5, 2.5 and 5.0 kWe total each. The DIPS architecture is assumed to be developed at the smallest module size (0.5 kWe), in spite of the fact that the 2.5 and 5.0 kWe systems only contain 2.5 kWe modules. The 2.5 and 5.0 kWe power systems will be developed based on the 0.5 kWe module size, but with a nominal 5 ($N_P$-1) $M delta "scaleup" development surcharge cost. $N_P$ in this case is 3, since the architecture contains 3 power module classes (0.5, 2.5, 5.0 kWe).

Factor 1.5 is the wrap factor, as above in Production cost

1.3.1.5 Development Repeat Factor Assumptions. The "development repeat" factor $F_i$ accounts for subsystem development under various state-of-the-art conditions; i.e., from developing a brand new technology to resurrecting or modifying an already established technology. The factors are defined as follows:

$F_i$ = Development repeat cost factor of subsystem i

$F_i$ = 1.0 new development (e.g., SSF EPS as seen in 1986)

$0.1<F_i<1.0$ modified subsystem development

$F_i$ = 0.1 Updated/restarted subsystem development (e.g., SSF EPS similar system as seen in 1995)

$F_i$ = 0 No development required (existing technology) (e.g., SSF EPS as seen in 2000, assuming SSF EPS was developed as planned.)

The bases for these factors are as follows:

- Basis for Near-Term Power Technology Options:
  1. The development program for the SSF/EPS has been completed prior to platform architecture implementation: All near-term $F_i$=0.1.
  2. Development programs for 2.5 kWe DIPS and SP-100 have not been completed prior to platform architecture implementation: all near term $F_i$=1.0 ( program cost is charged against platform architecture)
- Basis for Mid- and Far-Term Power Technology Options
  - Minor upgrades of near term technologies: $F_i$=0.1

    (Based on: F-1 and J-2, (Ref. 9), and NERVA, (Ref.10), restart estimates with upgrading: $F_i$=0.1 to 0.2)
  - Major technology enhancements of mid term or far term technologies: $F_i$=0.5.

    (Based on: engineering judgement that technology enhancement is about 50% of new technology program cost)

The next two subsections contain the inputs and LCC algorithms CERs for the PV/Battery and PV/RFC space power subsystems).

1.3.1.6 Inputs for PV Subsystem/LCC Cost Algorithms.

- Total solar cell power system output at the beginning of life ($KW_{BOL}$) or 5 years later ($KW_{BOL+5}$)
- Solar cell material (B/A) (see subsection 1.3.1.7 for input)
- Solar cell type ($K_{35}$) (see subsection 1.3.1.7 for input)
- Number of PV modules ($N_W$) - For SSF $N_W$ = 4, each with 2 wings or 8 blankets)
- Battery type ($K_9$, $K_{10}$) (see subsection 1.3.1.7 for input)
- Total power system battery/RFC energy storage requirement (W hrs)
- Total power system electrical power at user ($KW_e$)
- Number of batteries/RFCs per power system ($N_B$ and $N_R$)
- Power system drag area (A in $m^2$)
- Platform location in space (LEO, GEO, Moon surface, Mars surface)
- Platform mission life (yrs)
- Subsystem life (yrs)
- Development repeat factors for each subsystem, $F_i$

TABLE 1-7. REPEAT DEVELOPMENT COST FACTORS ($F_i$) FOR PV/BATTERY AND PV/RFC SYSTEMS

| PV/Battery and PV/RFC Systems | | | | | |
|---|---|---|---|---|---|
| **i** | **System** | **Near-Term Technology** | **Mid-Term Technology** | **Far-Term Technology** | **Explanation** |
| 1 | Power generation | GaAs/Ge (Inact) Planar $F_1=0.1$ | AlGaAs/Ge (Act.) Planar $F_1=1.0$ | GaAs/GaSb (Tand.) Concentrator $F_1=1.0$ | Solar Cell Material Solar Cell Type |
| 2 | Energy Storage - Batteries | NiH2 $F_2=0.1$ | NaS $F_2=1.0$ | NaS $F_2=0.5$ | Battery Type |
| | - RFC | High Press./2 yrs $F_2=0.1$ | High Press./5 yrs $F_2=0.5$ | Cryo/7 yrs $F_2=1.0$ | High Pressure or Low Press. Cryo |
| 3 | Thermal Control | Space Station Type $F_3=0.1$ | Heat Pipes $F_3=0.5$ | Heat Pipes $F_3=1.0$ | Radiator Type |
| 4 | Power Control | Space Station Type $F_4=0.1$ | Advanced $F_4=0.5$ | Advanced $F_4=1.0$ | Computer/Sensor/ Software Type |
| 5 | PMAD | $\eta=0.90$ $F_5=0.1$ | $\eta=0.92$ $F_5=0.5$ | $\eta=0.94$ $F_5=0.5$ | Electrical Eff. |

Note: $F_i$ factors were developed using engineering technical/cost judgments and are based on the rationale, groundrules and assumptions discussed in Subsection 1.3.1.5.
The assumption in this table is that the space station subsystems have been developed.

1.3.1.7 PV Power System Cost Estimation Relationships (CERs). All CERs are either directly taken from, aggregated or simplified versions of those shown in Ref. 4.

POWER GENERATION

Structure

$$C_U = C_P = 0.493\,(KW_{BOL+5})$$

$$C_D = 0.24\,(KW_{BOL})F_i$$

KW Ratio:

$\left(\frac{BOL+5}{BOL}\right)$ = 0.88 for Si cells, assumed to be the same for all other type cells (simplification).

$C_U$ = Flight Unit Cost, M$

$C_P$ = Flight Subsystem Cost, M$

$C_D$ = Development Cost, M$

Solar Panels

$$C_P = \frac{B}{A}(KW_{BOL}+5) = 0.695\,(KW_{BOL}+5) \text{ for silicon cells}$$

$$C_D = \frac{K_{35}}{5.55}\left(\frac{KW_{BOL}}{N_W}\right)^{0.5} F_i$$

$\frac{B}{A}$ = Ratio of specific solar panel unit cost ( $\frac{K\$}{m^2}$) divided by specific solar panel power generation ( $\frac{W}{m^2}$). This ratio varies from 0.6 to 0.9 for different solar cell types (Ref. 4)

$N_W$ = Number of solar panel modules in one power system (e.g., SSF at manned capability had four modules; see Ref. 4 for definition of modules).

$K_{35}$ = Integrated Array System Development Cost (from Ref. 4.)
= $44M for Planar
= $67M for Concentrator

ENERGY STORAGE

Battery + BCDU

$$C_U = 3.31\text{x}10^{-4}\, K_9\,(\text{WHRS}) + 0.384\left(\frac{KW_e}{N_B}\right)^{0.78} + 0.2$$

$$C_P = N_B C_U$$

$$C_D = \left[50\,K_{10} + 3.9\left(\frac{KW_e}{N_B}\right)^{0.67} + 6.7\right] F_i$$

$N_B$ = Number of batteries in one power system

$K_9$, $K_{10}$ = Battery type dependent constants

| Battery Type | $K_9$ | $K_{10}$ |
|---|---|---|
| $Ni\text{-}H_2$ | 1.0 | 1.0 |
| Ni-Cd | 0.5 | 0.02 |
| Na-S | 0.6 | 0.44 |
| Ag-Zn | 0.0127 | 0.02 |

RFC

$$C_U = 4.95+0.32\left(\frac{KW_e}{N_R}\right)+0.0387\left(\frac{KW\ HRS}{N_R}\right)^{0.5}$$

$$C_P = N_R C_U$$

$$C_D = 9.77\left(\frac{KW_e}{N_R}\right)^{0.4} F_i+1.7\ C_U$$

$N_R$ = Number of RFC Units in one power system

THERMAL CONTROL

$$C_U = 0.587\left(\frac{KW_e}{N_W}\right)^{0.6}+0.24\left(\frac{KW_e}{N_W}\right)$$

$$C_P = N_W C_U$$

$$C_D = 2.6\left(\frac{KW_e}{N_W}\right)^{0.6} F_i + 0.6\left(\frac{KW_e}{N_W}\right)$$

POWER CONTROL

$$C_U = 0.45$$

$$C_P = 0.45\ N_W$$

$$C_D = 128\left(\frac{KW_e}{100}\right)^{0.65} F_i$$

PMAD

$$C_U = 0.71\left(\frac{KW_e}{N_W}\right)^{0.78}$$

$$C_P = C_U N_W$$

$$C_D = 12.34\left(\frac{KW_e}{N_W}\right)^{0.65} F_i$$

The next two subsections contain the inputs and LCC algorithms (CERs) for the dynamic isotope power subsystems.

1.3.1.8 Inputs for DIPS System LCC Cost Algorithms.

- Total power system electrical power at user ($KW_e$)
- Number of DIPS modules, $N_D$

| | |
|---|---|
| if $2.5<KW_e$: | Multiple DIPS modules of 2.5 $KW_e$ each |
| if $1.0<KW_e<2.5$: | One DIPS module of 2.5 $KW_e$, derated |
| if $0.5\leq KW_e<1.0$: | One DIPS module of actual $KW_e$ value |

- Development repeat factors for each subsystem, $F_i$
- Cycle efficiency, $\eta_c$

TABLE 1-8. REPEAT DEVELOPMENT COST FACTORS ($F_i$) FOR DIPS

| DIPS | | | | | |
|---|---|---|---|---|---|
| **i** | **System** | **Near-Term Technology** | **Mid-Term Technology** | **Far-Term Technology** | **Explanation** |
| 1 | Power generation | $F_1$=1.0 | $F_1$=0.5 | $F_1$=1.0 | Increasing Temperatures of Heat Source Units |
| 2 | Power Conversion | 1133<br>$F_2$=1.0 | 1300<br>$F_2$=0.5 | 1450<br>$F_2$=1.0 | Converter hot side inlet temp. (K) Same for CBC and Stirling |
| 3 | Heat Rejection | $F_3$=1.0 | $F_3$=0.1 | $F_3$=0.1 | Current DIPS has a pumped loop radiator. NT, MT, FT radiators will have heat pipes |
| 4 | Power Processing Control Assembly (PPCA) | $F_4$=1.0 | $F_4$=0.1 | $F_4$=0.1 | No significant change in PPCA technology |

Note: $F_i$ factors were developed using engineering technical/cost judgments and are based on the rationale, groundrules and assumptions discussed in Subsection 1.3.1.5.
The assumption in this table is that the previous DIPS program has been cancelled and needs to be resurrected again.

1.3.1.9 DIPS Cost Estimating Relationships (CERs). All CERs are either directly taken from, aggregated or simplified versions of those shown in Ref. 4.

POWER GENERATION

Heat Source Unit (HSU)

$$C_P = 0.0625\left(\frac{KW_e}{\eta_c}\right)$$

$$C_D = 8.0\ F_i + 0.156\left(\frac{KW_e}{\eta_c}\right)$$

POWER CONVERSION

CBC

$$C_P = 0.1946\ KW_e + 0.7644$$

$$C_D = 20\ F_i + 2.5\ C_P$$

Stirling

$$C_P = 0.3892\ KW_e + 1.5288)$$

$$C_D = 40\ F_i + 2.5\ C_P$$

HEAT REJECTION (RADIATOR)

$$C_P = 0.0574\ (KW_e)^{0.63}$$

$$C_D = 3.75\ (KW_e)^{0.6} F_i$$

PPCA

$$C_P = 1.0$$

$$C_D = 4.0\ F_i$$

$C_P$ = Flight Subsystem Cost, M$
$C_D$ = Development Cost, M$
PPCA = Power Processing & Control Assembly

The next two subsections contain the inputs and LCC algorithms (CERs) for the liquid metal power reactor subsystems.

1.3.1.10 Inputs for LMR Subsystem LCC Algorithms.

- Total electrical power of one reactor at user ($KW_e$) = ($KW_{th}$) $\eta_c$
- Overall system efficiency, $\eta_c$
- Number of active reactor modules, $N_A$
- Number of standby reactor modules, $N_S$
- Reactor life before replacement, years, see Figure 1-17 for SP-100 reactor life characteristics (from Ref. 5)
- Radiator inlet temperature, $T_{RI}$ (K)
- Development repeat factors for each subsystem, $F_i$ (Table 1-9)

TABLE 1-9. REPEAT DEVELOPMENT COST FACTORS ($F_i$) FOR LMR/CBC

| | | LMR/CBC | | | |
|---|---|---|---|---|---|
| i | System | Near-Term Technology | Mid-Term Technology | Far-Term Technology | Explanation |
| 1 | Power generation (Reactor) | SP-100/CBC $F_1$=1.0 | High Temp Reactor $F_1$=0.5 | High Temp Reactor $F_1$=1.0 | High Temp. Reactors (same life as SP-100) |
| 2 | Power Conditioning | $F_2$=1.0 | $F_2$=0.5 | $F_2$=0.5 | Higher Electrical Efficiencies |
| 3 | Power Distribution | $F_3$=1.0 | $F_3$=0.5 | $F_3$=0.5 | Higher Electrical Efficiencies |
| 4 | Power Conversion | $F_4$=1.0 | $F_4$=0.5 | $F_4$=0.5 | Higher Turbine Inlet Temperatures |
| 5 | Heat Transport / Rejection | $F_5$=1.0 | $F_5$=0.5 | $F_5$=0.1 | Higher Heat Rejection Temperatures |
| 6 | Power System Control | $F_6$=1.0 | $F_6$=0.5 | $F_6$=1.0 | Computer/Sensor/ Software Advancement |

Note: Fi factors were developed using engineering, technical/cost judgments and are based on the rationale, groundrules and assumptions discussed in subsection 1.3.1.5.
The assumption in this table is that the previous SP-100 program has been cancelled and needs to be resurrected again.

1.3.1.11 LMR Cost Estimating Relationships (CERs). All CERs are either directly taken from, aggregated or simplified versions of those shown in Ref. 5.

POWER GENERATION

$$C_U = C_P = 12.6 \quad \text{for } 500 < KW_{th} < 1000$$

$$C_U = C_P = 12.6\left(\frac{KW_{th}}{1000}\right)^{0.2} \quad \text{for } 1000 < KW_{th} < 6000$$

$$C_D = \left[203 + 49.4\left(\frac{KW_{th}}{1000}\right)^{0.1}\right] F_i + 2.0\, C_U$$

$C_U$ = Flight Unit Cost, M$

$C_P$ = Flight Subsystem Cost, M$

$C_D$ = Development Cost, M$

POWER CONDITIONING

$$C_U = 0.0765\left(\frac{KW_e}{N_A}\right)^{0.7}$$

$$C_P = (N_A + N_S)\, C_U$$

$$C_D = 2.156\left(\frac{KW_e}{N_A}\right)^{0.6} F_i$$

POWER DISTRIBUTION

$$C_U = C_P$$

$$C_P = 13.7\left(\frac{KW_e}{100}\right)^{0.8}$$

$$C_D = 22.1\left(\frac{KW_e}{100}\right)^{0.67} F_i$$

POWER CONVERSION (CBC)

$$C_U = 0.4\, K_T\left(\frac{KW_e}{N_A}\right)^{0.85} \quad ; \quad K_T = 1 \text{ for } T_T < 990K$$

$$C_P = (N_A + N_S)\, C_U \quad ; \quad K_T = 2 \text{ for } T_T > 990K$$

$$C_D = 48.3\, F_i + 2.5\, C_U$$

HEAT TRANSPORT/REJECTION

$$C_U = 0.18\ F_i + 0.517\left[\frac{KW_{th}(1-\eta c)}{N_A}\right]^{0.63}$$

$$C_P = (N_A + N_S)C_U$$

$$C_D = 17.1\ F_i + 34.4 + 1.739\left[\frac{KW_{th}(1-\eta c)}{N_A}\right]^{0.63}$$

POWER SYSTEM CONTROL

$$C_U = C_P$$

$$C_P = 8.4$$

$$C_D = 84\left(\frac{KW_e}{100}\right)^{0.65} F_i$$

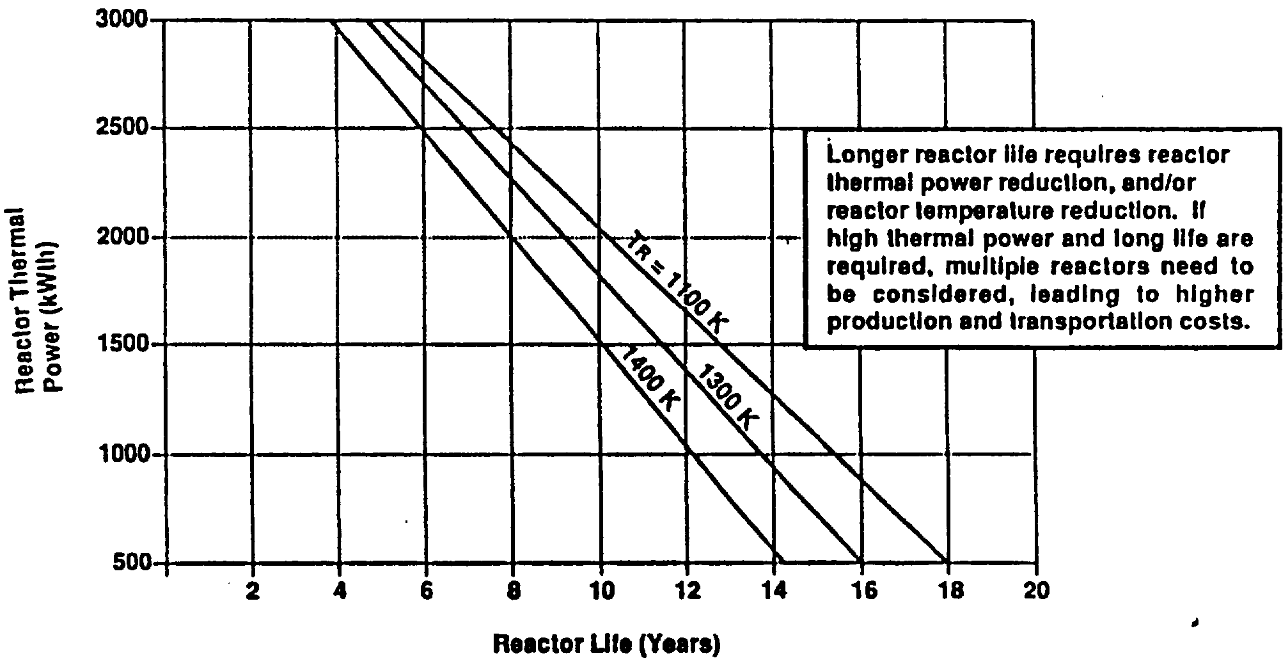



Figure 1-17. Reactor Life Characteristics (SP-100)

## 1.4 LCC SPREADSHEET

A spreadsheet was used to implement the LCC models described in Section 1.3 and assess power system technologies. Results from the DIPS/CBC spreadsheet are presented in the following section. The spreadsheet consists of three sections which include input parameters, system requirements and acquisition cost, and architecture requirements.

The input section of the spreadsheet lists technology parameters, development repeat factors, number of missions, mission life requirements, and minimum and maximum development power levels for a particular timeframe. The technology parameters and development repeat factors are discussed in the previous section (1.3). The mission life requirements are presented in a matrix format. Each value of the matrix is mission life requirement for a power level at a location (LEO, GEO, Moon, or Mars) and for a particular timeframe (near, mid, and far term). The mission life data is then compared with the system hardware life parameters to determine replacement cost for the architecture.

Minimum and maximum system power levels as well as the number of power module classes (npmc) are also provided as input to the spreadsheet. The development cost for a given timeframe is based on the corresponding power requirements for that timeframe and power module sizes.

The system requirements and acquisition cost section of the spreadsheet presents the system power requirements and development and production costs for each timeframe. The system power requirements determine the number of power modules and both are listed in the spreadsheet. Also included with the system power requirements are the number of power modules for each power level. Note that the power level, number of modules, and number of required power systems are LCC input parameters. This data as well as the other input parameters are used to compute the development and production costs for each timeframe. The development and production costs are given in terms of subsystem and system total. Production costs are given for each power level and are based on production of a single power system. Development costs are based on the minimum power module size as a ground rule.

The spreadsheet calculates transportation costs, replacement costs, and architecture LCC totals. The transportation costs are given in a matrix for each platform destination and each timeframe. These costs are based on the number of required power systems, specific power system mass from the input technology parameters and the specific transportation cost for a given location. Next the replacement cost is displayed in a matrix format identical to that of the mission life requirement matrix. The values of the matrix are the replacement cost of each system power level at each platform destination for all three timeframes. The architecture totals summarize the development, production, transportation, replacement, and reboost cost for each timeframe. Reboost cost is applicable to and hence determined for LEO power systems only.

## 1.5 LCC AND TECHNOLOGY ASSESSMENT RESULTS

Results from the application of the LCC methodology to an example case are discussed in the following section. The numerical evaluation of the LCC for a DIPS/CBC power system architecture was performed using Microsoft Excel spreadsheet software.

### 1.5.1 DIPS/CBC ASSESSMENT

The DIPS/CBC technology is selected for demonstration of the methodology. LCCs are calculated and compared to assess different strategies for development of this technology. However, it is noted that this method of LCC evaluation is generally applicable to all technologies; and the LCCs could be used to compare different strategies for a given technology as well as to compare benefits or cost competitiveness of different technologies.

A mission architecture of lunar surface missions requiring up to 15 kWe of power is selected for the demonstration. The architecture consists of 5 platforms (spacecraft) for near-term (NT), 6 platforms for mid-term (MT) and 4 platforms for far-term (FT) missions. Three technology implementation strategies are considered; the first is the reference or baseline for the comparison. The strategies which provide insight into allowable development costs are:

1. No Technology Development. Missions in all timeframes use NT technology (baseline), with minimal or no development costs. This represents one extreme for development.

2. Technical Development Limited to MT: NT missions use NT technology and MT and FT missions use MT technologies. This limits the development costs and allows some improvements in performance. This represents the middle of the range for development.

3. Continued Development to FT: NT missions use NT technology, MT and FT missions use MT and FT technologies respectively. This represents the other extreme for development.

LCCs were calculated for each strategy including all power systems within the mission architecture. Costs for all timeframes are based on constant dollar value at the end of the year 1992. Architecture cost is the total power system cost for all missions in the architecture. The LCC consists of (1) Development, (2) Hardware production and fuel cost, (3) Transportation, (4) Replacement cost and (5) Reboost cost. The spreadsheet calculates these separately to arrive at the total LCC for an architecture. However, for this architecture, the replacement cost is zero because hardware life is considered adequate for the set of missions, and reboost cost is zero because the missions are non-LEO missions. Power system modularization is considered to keep the costs low. Modules of 0.5, 1.0 and 2.5 kWe sizes are used in spacecraft for each timeframe depending on each spacecraft power requirement. The DIPS/CBC technology is assumed to require $67M for a 0.5 kWe system development and for NT mission flight readiness. Subsequent development costs are based on 2.5 kWe modules. Production costs include both hardware production cost and fuel cost which is particularly high for DIPS systems. Transportation costs are based on system mass. The results are presented and discussed below.

Tables 1-10 through 1-12 present the evaluation of the first (baseline) strategy. Table 1-10 lists the technology parameters, development cost factors and mission life requirements, which are all inputs to the spreadsheet. The minimum and maximum power requirements shown are respective sizes, and the npmc is the number of different module sizes in each timeframe. Since there are no missions in LEO, GEO or Mars, all values for these locations are listed as zero in the following tables to show that the spreadsheet is capable of including them in the analysis. Table 1-11 lists additional inputs which include the number of spacecraft at each power level and the size and number of modules on each spacecraft. Results from the calculation of production and development costs in each timeframe are presented as outputs of the spreadsheet. Table 1-12 lists the results from the calculation of transportation and reboost costs as well as the total LCC at the architecture level. The results show that the architecture power system costs are $1.55B, $2.71B and $2.59B, respectively, for the NT, MT and FT missions for a total of $6.85 B across all time frames. These costs provide the basis for comparison with the other strategies and, in general, evaluation of the benefits of further technical development.

Tables 1-13 through 1-15 present the evaluation of the second strategy, the strategy of moderate development. These tables are respectively similar to Tables 1-10 through 1-12. Moderate development cost of $27M is shown for the MT technology upgrade. The development effort assumed utilization of earlier development, as shown by the development repeat cost factors of 0.5 and 0. Efficiency of DIPS/CBC conversion is improved from 22% to 26%. There would be a corresponding savings in fuel consumption and, hence, fuel cost for MT and FT missions. There is no reduction in specific mass of 167 kg/kWe and, hence, no savings in transportation cost. Therefore, cost tradeoff in this strategy is between higher development cost and savings in fuel cost. LCCs are $1.55B, $2.47B and $2.34B for the NT, MT and FT missions, respectively, for a total architecture LCC of $6.37B for this strategy. There are savings of $0.23B in the MT LCC and $0.25B in the FT LCC for a total savings of $0.48B for the architecture. This strategy shows an improvement over the baseline considering $27M investment against $480M savings.

Tables 1-16 through 1-18 present the evaluation of the third strategy. Relatively more aggressive development is considered for LT development at a cost of $48M. The conversion efficiency is further improved by 1% to 27% and the specific mass is reduced from 167 to 137 kg/kWe. Accordingly, LT LCC reduced to $2.17B, a savings of $0.17B from the second strategy. Again, these savings show an improvement over the earlier strategy, considering $48M investment against $170M saving.

Figure 1-18 shows different cost components and LCCs for the third (best) strategy for the NT, MT and FT missions. Figure 1-19 shows the cost savings due to different strategies, again demonstrating superiority of continued development. Figure 1-20 shows the architecture LCC and its components for this strategy.

Cost estimates here are based on not discounting the dollar value for inflation. Higher development costs due to inflation tend to increase the expenses compared to the baseline strategy. However, the savings in fuel and transportation costs also would increase in the same proportion. Therefore, continued development continues to be more attractive.

Some important conclusions are as follows:

- Architecture LCC is in the $6B to $7B range for the lunar surface missions considered.
- Continuous technical development offers the most cost savings, $650M compared to no development over a 35-year period.
- The LCC advantage is primarily due to savings in fuel cost and to some extent to savings in transportation cost.
- Development continues to be the better option even though the dollar value is discounted for MT and FT missions.

**DIPS/CBC LCC Spreadsheet**

| | Technology Parameters | | Near | Mid | Far |
|---|---|---|---|---|---|
| Pwr Conv | Hot-Side Temp | (K) | 1133 | 1133 | 1133 |
| | Type | | CBC | CBC | CBC |
| Heat Rej | Specific Area | (sqm/kWe) | 7 | 7 | 7 |
| System | Specific Mass | (kg/kWe) | 167 | 167 | 167 |
| | Efficiency | | 0.22 | 0.22 | 0.22 |
| | Life | (years) | 15 | 15 | 15 |
| Misc | E Factor | | 0.5 | 0.5 | 0.5 |
| | Plutonium Cost | | 8.5 | 8.5 | 8.5 |
| | Delta Cdp | | 5 | 5 | 5 |
| | Z Factor | | 0.75 | 0.75 | 0.75 |

| Development Repeat Cost Factors | Near | Mid | Far |
|---|---|---|---|
| Pwr Generation | 1 | 0 | 0 |
| Pwr Conversion | 1 | 0 | 0 |
| Heat Rejection | 1 | 0 | 0 |
| PPCA | 1 | 0 | 0 |

| Mission Life Requirement Matrix (yrs) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Near Term | | | | Mid Term | | | | Far Term | | | |
| Total kWe | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars |
| 0.5 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 1 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 2.5 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 5 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 10 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 15 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |

| Min and Max Power Requirements | | | |
|---|---|---|---|
| | Near | Mid | Far |
| kwe_max | 2.50 | 2.50 | 2.50 |
| kwe_min | 0.50 | 2.50 | 2.50 |
| npme | 3 | 1 | 1 |

Table 1-10 DIPS/CBC Spreadsheet: Technology Parameters Inputs
(Baseline Case - No Technology Upgrades for MT and FT Missions)

**Near Term System Power Requirements**

| Total kWe | # modules | kWe/mod | LEO | GEO | Moon | Mars | Total |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 0.5 | 0 | 0 | 1 | 0 | 1 |
| 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 2.5 | 1 | 2.5 | 0 | 0 | 0 | 0 | 0 |
| 5 | 2 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 10 | 4 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 15 | 6 | 2.5 | 0 | 0 | 1 | 0 | 1 |

Development based on 0.50 kWe level

Add $10 M for 3 power module classes

**Near Term Production and Development Costs**

| Subsystem Cost | Cd | Cp @ Power Level, kWe ($M) 0.5 | 1 | 2.5 | 5 | 10 | 15 |
|---|---|---|---|---|---|---|---|
| Pwr Generation | 8.35 | 0.14 | 0.28 | 0.71 | 1.42 | 2.84 | 4.26 |
| Pwr Conversion | 22.15 | 0.86 | 0.96 | 1.25 | 2.50 | 5.00 | 7.51 |
| Heat Rejection | 2.47 | 0.04 | 0.06 | 0.10 | 0.20 | 0.41 | 0.61 |
| PPCA | 4.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Summation | 36.98 | 2.04 | 2.30 | 3.06 | 5.13 | 9.25 | 13.38 |
| System Costs | 67.00 | 17.55 | 32.43 | 77.04 | 152.58 | 303.65 | 454.73 |

**Mid Term System Power Requirements**

| Total kWe | # modules | kWe/mod | LEO | GEO | Moon | Mars | Total |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 0.5 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2.5 | 1 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 5 | 2 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 10 | 4 | 2.5 | 0 | 0 | 2 | 0 | 2 |
| 15 | 6 | 2.5 | 0 | 0 | 2 | 0 | 2 |

Development based on 2.50 kWe level

Add $0 M for 1 power module classes

**Mid Term Production and Development Costs**

| Subsystem Cost | Cd | Cp @ Power Level, kWe ($M) 0.5 | 1 | 2.5 | 5 | 10 | 15 |
|---|---|---|---|---|---|---|---|
| Pwr Generation | 0.00 | 0.14 | 0.28 | 0.71 | 1.42 | 2.84 | 4.26 |
| Pwr Conversion | 0.00 | 0.86 | 0.96 | 1.25 | 2.50 | 5.00 | 7.51 |
| Heat Rejection | 0.00 | 0.04 | 0.06 | 0.10 | 0.20 | 0.41 | 0.61 |
| PPCA | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Summation | 0.00 | 2.04 | 2.30 | 3.06 | 5.13 | 9.25 | 13.38 |
| System Costs | 0.00 | 17.55 | 32.43 | 77.04 | 152.58 | 303.65 | 454.73 |

**Far Term System Power Requirements**

| Total kWe | # modules | kWe/mod | LEO | GEO | Moon | Mars | Total |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 0.5 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2.5 | 1 | 2.5 | 0 | 0 | 0 | 0 | 0 |
| 5 | 2 | 2.5 | 0 | 0 | 0 | 0 | 0 |
| 10 | 4 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 15 | 6 | 2.5 | 0 | 0 | 3 | 0 | 3 |

Development based on 2.50 kWe level

Add $0 M for 1 power module classes

**Far Term Production and Development Costs**

| Subsystem Cost | Cd | Cp @ Power Level, kWe ($M) 0.5 | 1 | 2.5 | 5 | 10 | 15 |
|---|---|---|---|---|---|---|---|
| Pwr Generation | 0.00 | 0.14 | 0.28 | 0.71 | 1.42 | 2.84 | 4.26 |
| Pwr Conversion | 0.00 | 0.86 | 0.96 | 1.25 | 2.50 | 5.00 | 7.51 |
| Heat Rejection | 0.00 | 0.04 | 0.06 | 0.10 | 0.20 | 0.41 | 0.61 |
| PPCA | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Summation | 0.00 | 2.04 | 2.30 | 3.06 | 5.13 | 9.25 | 13.38 |
| System Costs | 0.00 | 17.55 | 32.43 | 77.04 | 152.58 | 303.65 | 454.73 |

Table 1-11 DIPS/CBC Spreadsheet: System Requirements Inputs (Baseline Case - No Technology Upgrades for MT and FT Missions)

| Transportation Costs | | | | |
|---|---|---|---|---|
| Destination | $K / kg | Near | Mid | Far |
| LEO | 5 | 0 | 0 | 0 |
| GEO | 20 | 0 | 0 | 0 |
| Moon | 100 | 526 | 960 | 919 |
| Mars | 200 | 0 | 0 | 0 |
| Total | | 526 | 960 | 919 |

| Replacement Cost | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Near Term | | | | Mid Term | | | | Far Term | | | |
| Total kWe | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars |
| 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Totals | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Architecture Totals | Near | Mid | Far |
|---|---|---|---|
| Development Cost | 67 | 0 | 0 |
| Production Cost | 961 | 1746 | 1668 |
| Transportation Cost | 526 | 960 | 919 |
| Replacement Cost | 0 | 0 | 0 |
| Reboost Cost | 0 | 0 | 0 |
| Totals | 1,554 | 2,707 | 2,586 |

Table 1-12 DIPS/CBC Spreadsheet: Architecture Cost Estimates
(Baseline Case - No Technology Upgrades for MT and FT Missions)

DIPS/CBC LCC Spreadsheet

| | Technology Parameters | | Near | Mid | Far |
|---|---|---|---|---|---|
| Pwr Conv | Hot-Side Temp | (K) | 1133 | 1300 | 1300 |
| | Type | | CBC | CBC | CBC |
| Heat Rej | Specific Area | (sqm/kWe) | 7 | 5 | 5 |
| System | Specific Mass | (kg/kWe) | 167 | 167 | 167 |
| | Efficiency | | 0.22 | 0.26 | 0.26 |
| | Life | (years) | 15 | 15 | 15 |
| Misc | E Factor | | 0.5 | 0.5 | 0.5 |
| | Plutonium Cost | | 8.5 | 8.5 | 8.5 |
| | Delta Cdp | | 5 | 5 | 5 |
| | Z Factor | | 0.75 | 0.75 | 0.75 |

| Development Repeat Cost Factors | Near | Mid | Far |
|---|---|---|---|
| Pwr Generation | 1 | 0.5 | 0 |
| Pwr Conversion | 1 | 0.5 | 0 |
| Heat Rejection | 1 | 0.1 | 0 |
| PPCA | 1 | 0.1 | 0 |

Mission Life Requirement Matrix (yrs)

| | Near Term | | | | Mid Term | | | | Far Term | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total kWe | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars |
| 0.5 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 1 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 2.5 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 5 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 10 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 15 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |

Min and Max Power Requirements

| | Near | Mid | Far |
|---|---|---|---|
| kwe_max | 2.50 | 2.50 | 2.50 |
| kwe_min | 0.50 | 2.50 | 2.50 |
| npmc | 3 | 1 | 1 |

Table 1-13 DIPS/CBC Spreadsheet: Technology Parameters Inputs (Mid-Term Technology Upgrade Only)

**Near Term System Power Requirements**

| Total kWe | # modules | kWe/mod | LEO | GEO | Moon | Mars | Total |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 0.5 | 0 | 0 | 1 | 0 | 1 |
| 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 2.5 | 1 | 2.5 | 0 | 0 | 0 | 0 | 0 |
| 5 | 2 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 10 | 4 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 15 | 6 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| Development based on | | 0.50 | kWe level | | | | |
| Add | $10 M | for | 3 | power module classes | | | |

**Near Term Production and Development Costs**

| Subsystem Cost | Cd | Cp @ Power Level, kWe ($M) 0.5 | 1 | 2.5 | 5 | 10 | 15 |
|---|---|---|---|---|---|---|---|
| Pwr Generation | 8.35 | 0.14 | 0.28 | 0.71 | 1.42 | 2.84 | 4.26 |
| Pwr Conversion | 22.15 | 0.86 | 0.96 | 1.25 | 2.50 | 5.00 | 7.51 |
| Heat Rejection | 2.47 | 0.04 | 0.06 | 0.10 | 0.20 | 0.41 | 0.61 |
| PPCA | 4.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Summation | 36.98 | 2.04 | 2.30 | 3.06 | 5.13 | 9.25 | 13.38 |
| System Costs | 67.00 | 17.55 | 32.43 | 77.04 | 152.58 | 303.65 | 454.73 |

**Mid Term System Power Requirements**

| Total kWe | # modules | kWe/mod | LEO | GEO | Moon | Mars | Total |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 0.5 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2.5 | 1 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 5 | 2 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 10 | 4 | 2.5 | 0 | 0 | 2 | 0 | 2 |
| 15 | 6 | 2.5 | 0 | 0 | 2 | 0 | 2 |
| Development based on | | 2.50 | kWe level | | | | |
| Add | $0 M | for | 1 | power module classes | | | |

**Mid Term Production and Development Costs**

| Subsystem Cost | Cd | Cp @ Power Level, kWe ($M) 0.5 | 1 | 2.5 | 5 | 10 | 15 |
|---|---|---|---|---|---|---|---|
| Pwr Generation | 5.50 | 0.12 | 0.24 | 0.60 | 1.20 | 2.40 | 3.61 |
| Pwr Conversion | 10.00 | 0.86 | 0.96 | 1.25 | 2.50 | 5.00 | 7.51 |
| Heat Rejection | 0.65 | 0.04 | 0.06 | 0.10 | 0.20 | 0.41 | 0.61 |
| PPCA | 0.40 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Summation | 16.55 | 2.02 | 2.26 | 2.95 | 4.91 | 8.82 | 12.72 |
| System Costs | 27.04 | 15.29 | 27.90 | 65.73 | 129.96 | 258.42 | 386.88 |

**Far Term System Power Requirements**

| Total kWe | # modules | kWe/mod | LEO | GEO | Moon | Mars | Total |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 0.5 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2.5 | 1 | 2.5 | 0 | 0 | 0 | 0 | 0 |
| 5 | 2 | 2.5 | 0 | 0 | 0 | 0 | 0 |
| 10 | 4 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 15 | 6 | 2.5 | 0 | 0 | 3 | 0 | 3 |
| Development based on | | 2.50 | kWe level | | | | |
| Add | $0 M | for | 1 | power module classes | | | |

**Far Term Production and Development Costs**

| Subsystem Cost | Cd | Cp @ Power Level, kWe ($M) 0.5 | 1 | 2.5 | 5 | 10 | 15 |
|---|---|---|---|---|---|---|---|
| Pwr Generation | 0.00 | 0.12 | 0.24 | 0.60 | 1.20 | 2.40 | 3.61 |
| Pwr Conversion | 0.00 | 0.86 | 0.96 | 1.25 | 2.50 | 5.00 | 7.51 |
| Heat Rejection | 0.00 | 0.04 | 0.06 | 0.10 | 0.20 | 0.41 | 0.61 |
| PPCA | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Summation | 0.00 | 2.02 | 2.26 | 2.95 | 4.91 | 8.82 | 12.72 |
| System Costs | 0.00 | 15.29 | 27.90 | 65.73 | 129.96 | 258.42 | 386.88 |

Table 1-14 DIPS/CBC Spreadsheet: System Requirements Inputs
(Mid-Term Technology Upgrade Only)

**Transportation Costs**

| Destination | $K / kg | Near | Mid | Far |
|---|---|---|---|---|
| LEO | 5 | 0 | 0 | 0 |
| GEO | 20 | 0 | 0 | 0 |
| Moon | 100 | 526 | 960 | 919 |
| Mars | 200 | 0 | 0 | 0 |
| Total | | 526 | 960 | 919 |

**Replacement Cost**

| | Near Term | | | | Mid Term | | | | Far Term | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total kWe | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars |
| 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Totals | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Architecture Totals | Near | Mid | Far |
|---|---|---|---|
| Development Cost | 67 | 27 | 0 |
| Production Cost | 961 | 1486 | 1419 |
| Transportation Cost | 526 | 960 | 919 |
| Replacement Cost | 0 | 0 | 0 |
| Reboost Cost | 0 | 0 | 0 |
| Totals | 1,554 | 2,474 | 2,338 |

Table 1-15 DIPS/CBC Spreadsheet: Architecture Cost Estimates (Mid-Term Technology Upgrade Only)

**DIPS/CBC LCC Spreadsheet**

| | Technology Parameters | | Near | Mid | Far |
|---|---|---|---|---|---|
| Pwr Conv | Hot-Side Temp | (K) | 1133 | 1300 | 1450 |
| | Type | | CBC | CBC | CBC |
| Heat Rej | Specific Area | (sqm/kWe) | 7 | 5 | 4 |
| System | Specific Mass | (kg/kWe) | 167 | 167 | 137 |
| | Efficiency | | 0.22 | 0.26 | 0.27 |
| | Life | (years) | 15 | 15 | 15 |
| Misc | E Factor | | 0.5 | 0.5 | 0.5 |
| | Plutonium Cost | | 8.5 | 8.5 | 8.5 |
| | Delta Cdp | | 5 | 5 | 5 |
| | Z Factor | | 0.75 | 0.75 | 0.75 |

| Development Repeat Cost Factors | Near | Mid | Far |
|---|---|---|---|
| Pwr Generation | 1 | 0.5 | 1 |
| Pwr Conversion | 1 | 0.5 | 1 |
| Heat Rejection | 1 | 0.1 | 0.1 |
| PPCA | 1 | 0.1 | 0.1 |

| Mission Life Requirement Matrix (yrs) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Near Term | | | | Mid Term | | | | Far Term | | | |
| Total kWe | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars |
| 0.5 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 1 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 2.5 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 5 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 10 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |
| 15 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 | 0 | 0 | 15 | 0 |

| Min and Max Power Requirements | | | |
|---|---|---|---|
| | Near | Mid | Far |
| kwe_max | 2.50 | 2.50 | 2.50 |
| kwe_min | 0.50 | 2.50 | 2.50 |
| npmc | 3 | 1 | 1 |

Table 1-16 DIPS/CBC Spreadsheet: Technology Parameters Inputs (Mid- and Far-Term Technology Upgrades)

**Near Term System Power Requirements**

| Total kWe | # modules | kWe/mod | LEO | GEO | Moon | Mars | Total |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 0.5 | 0 | 0 | 1 | 0 | 1 |
| 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 2.5 | 1 | 2.5 | 0 | 0 | 0 | 0 | 0 |
| 5 | 2 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 10 | 4 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 15 | 6 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| Development based on | | 0.50 | kWe level | | | | |
| Add | $10 M | for | 3 | power module classes | | | |

**Near Term Production and Development Costs**

| | | Cp @ Power Level, kWe ($M) | | | | | |
|---|---|---|---|---|---|---|---|
| Subsystem Cost | Cd | 0.5 | 1 | 2.5 | 5 | 10 | 15 |
| Pwr Generation | 8.35 | 0.14 | 0.28 | 0.71 | 1.42 | 2.84 | 4.26 |
| Pwr Conversion | 22.15 | 0.86 | 0.96 | 1.25 | 2.50 | 5.00 | 7.51 |
| Heat Rejection | 2.47 | 0.04 | 0.06 | 0.10 | 0.20 | 0.41 | 0.61 |
| PPCA | 4.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Summation | 36.98 | 2.04 | 2.30 | 3.06 | 5.13 | 9.25 | 13.38 |
| System Costs | 67.00 | 17.55 | 32.43 | 77.04 | 152.58 | 303.65 | 454.73 |

**Mid Term System Power Requirements**

| Total kWe | # modules | kWe/mod | LEO | GEO | Moon | Mars | Total |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 0.5 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2.5 | 1 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 5 | 2 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 10 | 4 | 2.5 | 0 | 0 | 2 | 0 | 2 |
| 15 | 6 | 2.5 | 0 | 0 | 2 | 0 | 2 |
| Development based on | | 2.50 | kWe level | | | | |
| Add | $0 M | for | 1 | power module classes | | | |

**Mid Term Production and Development Costs**

| | | Cp @ Power Level, kWe ($M) | | | | | |
|---|---|---|---|---|---|---|---|
| Subsystem Cost | Cd | 0.5 | 1 | 2.5 | 5 | 10 | 15 |
| Pwr Generation | 5.50 | 0.12 | 0.24 | 0.60 | 1.20 | 2.40 | 3.61 |
| Pwr Conversion | 10.00 | 0.86 | 0.96 | 1.25 | 2.50 | 5.00 | 7.51 |
| Heat Rejection | 0.65 | 0.04 | 0.06 | 0.10 | 0.20 | 0.41 | 0.61 |
| PPCA | 0.40 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Summation | 16.55 | 2.02 | 2.26 | 2.95 | 4.91 | 8.82 | 12.72 |
| System Costs | 27.04 | 15.29 | 27.90 | 65.73 | 129.96 | 258.42 | 386.88 |

**Far Term System Power Requirements**

| Total kWe | # modules | kWe/mod | LEO | GEO | Moon | Mars | Total |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 0.5 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2.5 | 1 | 2.5 | 0 | 0 | 0 | 0 | 0 |
| 5 | 2 | 2.5 | 0 | 0 | 0 | 0 | 0 |
| 10 | 4 | 2.5 | 0 | 0 | 1 | 0 | 1 |
| 15 | 6 | 2.5 | 0 | 0 | 3 | 0 | 3 |
| Development based on | | 2.50 | kWe level | | | | |
| Add | $0 M | for | 1 | power module classes | | | |

**Far Term Production and Development Costs**

| | | Cp @ Power Level, kWe ($M) | | | | | |
|---|---|---|---|---|---|---|---|
| Subsystem Cost | Cd | 0.5 | 1 | 2.5 | 5 | 10 | 15 |
| Pwr Generation | 9.44 | 0.12 | 0.23 | 0.58 | 1.16 | 2.31 | 3.47 |
| Pwr Conversion | 20.00 | 0.86 | 0.96 | 1.25 | 2.50 | 5.00 | 7.51 |
| Heat Rejection | 0.65 | 0.04 | 0.06 | 0.10 | 0.20 | 0.41 | 0.61 |
| PPCA | 0.40 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Summation | 30.49 | 2.01 | 2.25 | 2.93 | 4.86 | 8.73 | 12.59 |
| System Costs | 47.94 | 14.83 | 26.98 | 63.43 | 125.35 | 249.20 | 373.05 |

Table 1-17 DIPS/CBC Spreadsheet: System Requirements Inputs (Mid- and Far-Term Technology Upgrades)

| Transportation Costs | | | | |
|---|---|---|---|---|
| Destination | $K / kg | Near | Mid | Far |
| LEO | 5 | 0 | 0 | 0 |
| GEO | 20 | 0 | 0 | 0 |
| Moon | 100 | 526 | 960 | 754 |
| Mars | 200 | 0 | 0 | 0 |
| Total | | 526 | 960 | 754 |

| Replacement Cost | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Near Term | | | | Mid Term | | | | Far Term | | | |
| Total kWe | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars | LEO | GEO | Moon | Mars |
| 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Totals | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Architecture Totals | Near | Mid | Far |
|---|---|---|---|
| Development Cost | 67 | 27 | 48 |
| Production Cost | 961 | 1486 | 1368 |
| Transportation Cost | 526 | 960 | 754 |
| Replacement Cost | 0 | 0 | 0 |
| Reboost Cost | 0 | 0 | 0 |
| Totals | 1,554 | 2,474 | 2,170 |

Table 1-18 DIPS/CBC Spreadsheet: Architecture Cost Estimates (Mid- and Far-Term Technology Upgrades)

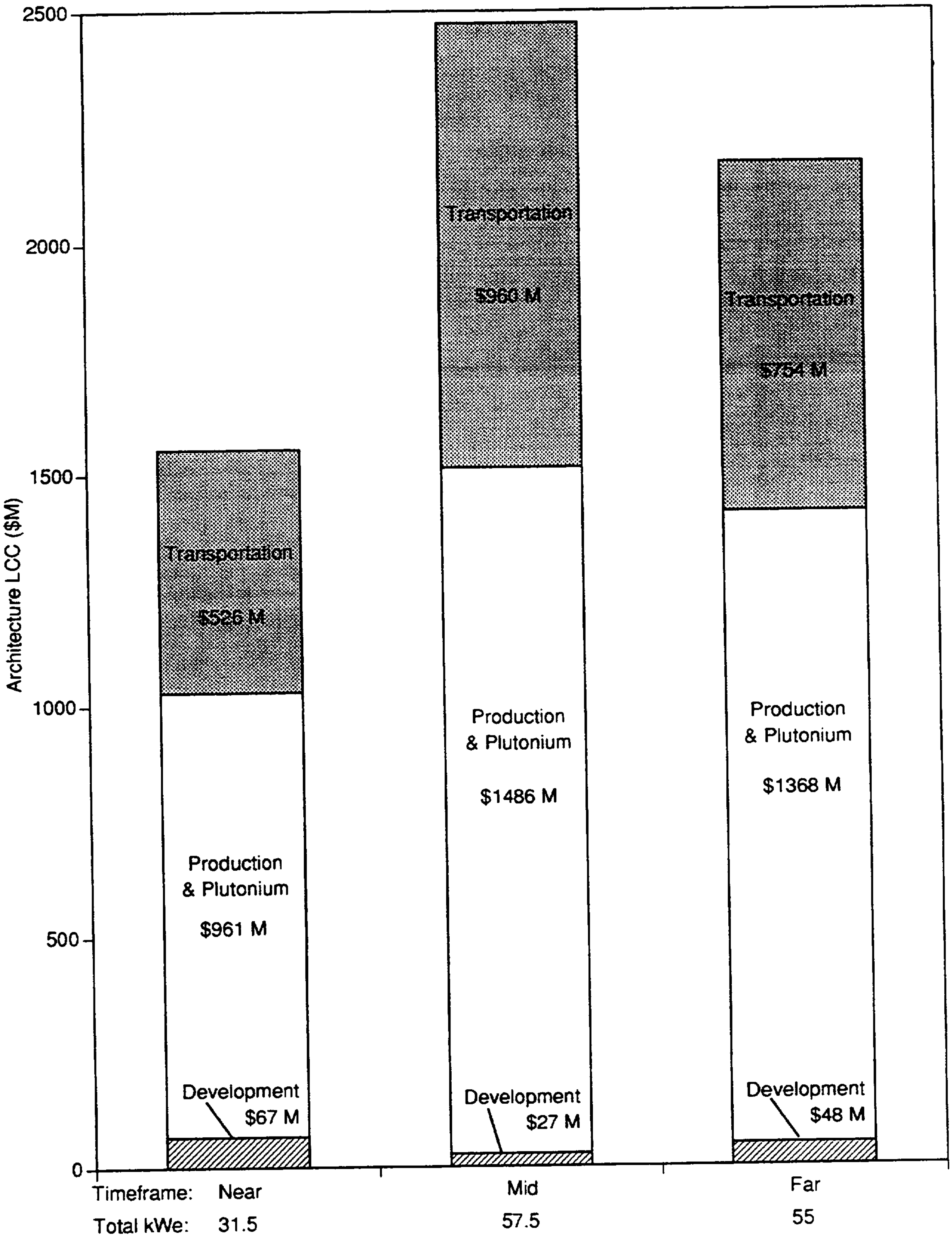



Figure 1-18 DIPS/CBC Architecture LCC for Two Technology Upgrades

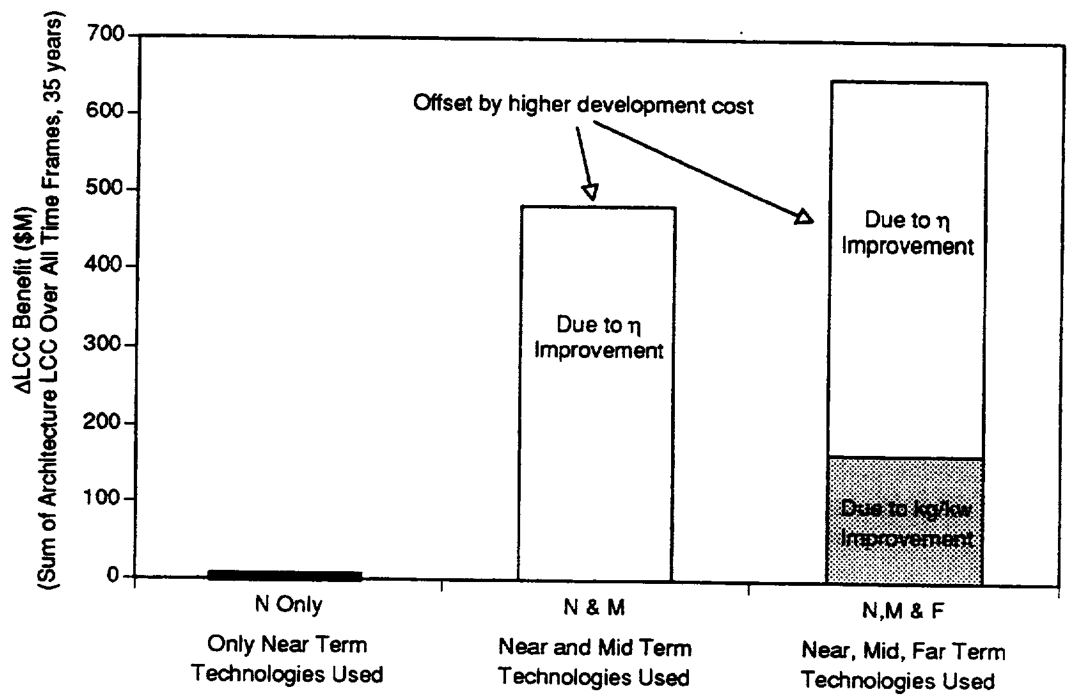



Figure 1-19 Relative DIPS/CBC System Architecture LCC Comparison for Different Technology Acquistion Strategies

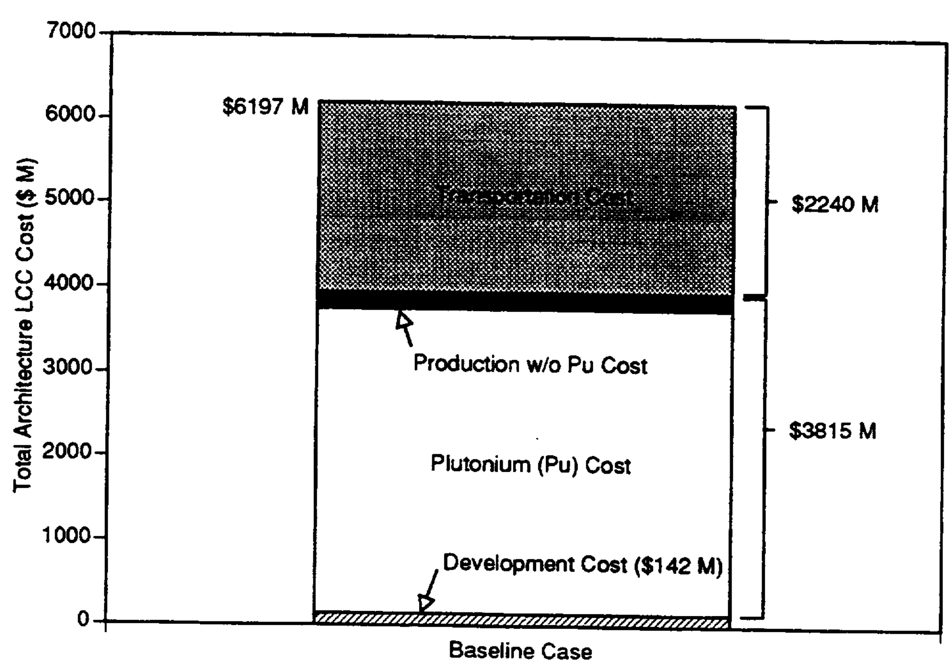



Figure 1-20 Total 35-Year DIPS/CBC Architecture LCC for Two Technology Upgrades (Sum of Figure 1-18 Costs)

## TASK 2.0 TECHNOLOGY DEVELOPMENT PLANS

The main objective of this task was to generate evolutionary technology development plans for the most attractive power technologies for future missions. The technology requirements, established in Task 1, were used to formulate technology development plans down to the subsystem level. The Task 2 effort essentially ran in parallel with Task 1. The following are the four major subtasks performed in Task 2:

- 2.1 Hardware Production Plan
- 2.2 Technology Issues and Gaps
- 2.3 Technology Programs
- 2.4 Development Plans

Advanced power systems listed in Table 1-1 for Earth orbital, lunar, and Mars applications included dynamic isotope, photovoltaic, and reactor concepts for power generation and regenerative fuel cell and battery for energy storage. In Task 2, hardware production requirements, current and past technology programs, technology issues and gaps for each system was examined and component and system development tasks were identified.

Development times to flight readiness for each power system were then estimated (Table 2-1). This information was then incorporated into technology development roadmaps for each candidate power system. An integrated development schedule is shown in Figure 2-1 for PV/RFC, Dynamic SP-100, and SD power systems. For development of the three systems, a uniform approach was taken covering component development, ground system development, qualification (reconfiguration for flight and testing), and flight (manufacture/assembly, acceptance testing, safety program, and launch support). Safety programs also were included for all nuclear and isotope systems.

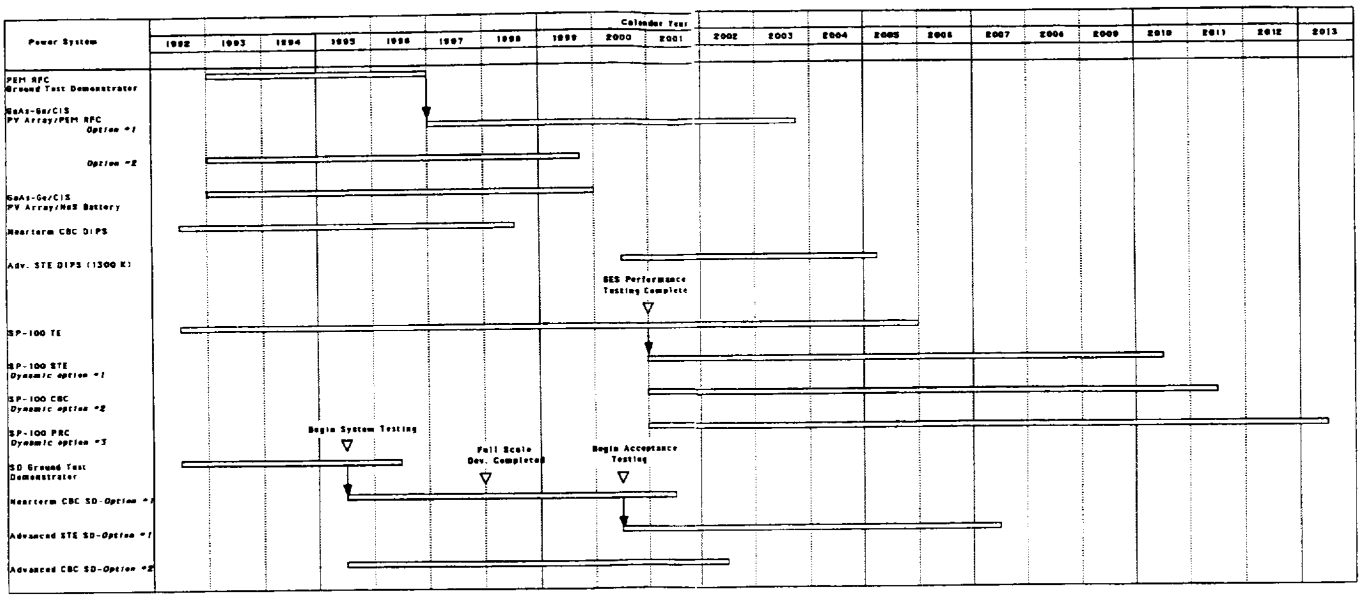



Figure 2-1. Integrated Development Schedule

TABLE 2-1 POWER SYSTEM ESTIMATED DEVELOPMENT TIMES

| Power System | Estimated Development Times (yrs)* |
|---|---|
| Near-term CBC DIPS | 6 |
| Advanced STE DIPS | 4.75** |
| PEM RFC | 6.75 |
| NaS Batteries | 7 |
| Near-term CBC SD | 6 |
| Advanced CBC SD | 7 |
| Advanced STE SD | 7+ |
| GaAs-Ge/CIS PV array/PEM RFC | 6.75 |
| GaAs-Ge/CIS PV array/NaS battery | 7 |
| Driver Fuel In-core TFE reactor | 7.5 |
| SP-100 TE | 13.5 |
| SP-100 CBC | 10.5++ |
| SP-100 STE | 9.5++ |
| SP-100 PRC | 13.5++ |

*To launch.

**Assumes prior development of Near-Term CBC DIPS.

+Assumes prior development of Near-Term CBC SD.

++Assumes prior development of SP-100 TE.

## GROUNDRULES

Power system concepts were considered only at the system and subsystem level. Technologies at the subsystem component level were not evaluated. Subsystems included the energy source, power conversion unit (PCU), energy storage, heat rejection, and power processing and control (PP&C). Power distribution was not considered (application and power system dependent). Integration of power systems with the loads also was not considered in the development plans (application and vehicle specific).

In general, each power system development plan was treated independently of the others to allow development of any single system. Advanced systems (1300 °K STE DIPS, STE SD, and SP-100 Dynamic) were assumed to follow development of a near-term or baseline system (CBC DIPS, near-term CBC SD, and SP-100 TE, respectively). Accordingly, prior development was considered for these advanced systems.

It is assumed that the same power systems will be used for both lunar and Mars applications. This forces the technologies to be ready earlier than necessary for Mars missions but improves the reliability for Mars missions.

It was assumed that power systems are developed such that expensive flight testing and verification is minimized. However, ground testing will be done on the component, subsystem, and system level to ensure reliability. Qualification testing was included for both flight subsystems and systems.

## TASK 2.1 HARDWARE PRODUCTION PLAN

A power system hardware production plan was developed based on the timing of the missions and projected life of hardware. The production plan showed number of power system modules required over the life of the mission, thereby impacting the LCC. The quantities or number of power system modules required by each platform are summarized in figures 1-13 and 1-14.

## TASK 2.2 TECHNOLOGY ISSUES AND GAPS

In Task 2.2 critical technology issues were identified and major technology gaps were outlined. This consisted of technology issues and gaps for the PEM RFC and NaS batteries (both for planetary surface mobile power), near-term CBC DIPS (1133 °K), advanced STE DIPS (1300 °K), GaAs-Ge/CIS PV array/PEM RFC, GaAs-Ge/CIS PV array/NaS battery, Driver Fuel In-core TFE reactor, SP-100 TE, Dynamic SP-100 (CBC, STE, and PRC PCUs), near-term CBC SD, advanced CBC SD, and advanced STE SD power systems. Appendices A to K describe these along with development road maps in significant detail. Tables 2-2 through 2-5 below, summarize the key issues and technology gaps for these power systems.

TABLE 2-2. SUMMARY OF KEY ISSUES AND TECHNOLOGY GAPS

| Technology | Issue | Technology Gaps |
|---|---|---|
| Near-term CBC DIPS | •Isotope cooling/Nuclear safety | •High emissivity coatings<br>•RHRS heat pipes<br>•Meltable MFI package |
| | •Lunar/Mars environment | •Coatings, getters, semi-permeable seals, dust protection, OSRs |
| | •Shock loading | •Gas-foil bearing performance<br>•Heat pipe design and verification testing |
| | •Alternator temperature | •High temperature alternator insulation |
| | •Isotope handling & disposal | •Fuel handling canister and tools |
| | •Recuperator heat transfer performance | •High performance laminar flow recuperator designs |
| | •Gas leakage | •Full-penetration inspectable welded boundaries<br>•Low-temperature dissimilar metal transition joints<br>•Meteoroid protection |
| Advanced STE DIPS (1300 °K) | •Protection of refractory metals in Stirling engine from Martian atmosphere | •High temperature coatings<br>•Vacuum enclosure |
| | •Stirling engine heater head life | •Life testing<br>•Long life refractory alloys |

TABLE 2-3. SUMMARY OF KEY ISSUES AND TECHNOLOGY GAPS (CONT'D)

| Technology | Issues | Technology Gaps |
|---|---|---|
| Near-term CBC SD | •Flux tailoring and the effect on receiver life | •Heat source design |
| | •Concentrator pointing accuracy, fabrication, and assembly | •Concentrator design and manufacture |
| | •TES canister manufacturing techniques; void formation during freezing; TES mass | •TES design and manufacture |
| | •Determination of receiver state-of-thermal-charge | •Control methodology |
| | •EMI from alternator | •Electronics shielding |
| Advanced CBC SD | •Concentrator mass, ease of deployability, and surface smoothness | •Reflective concentrator design |
| | •Integration of PCU and receiver | •Integrated unit testing |
| | •TES canister manufacturing techniques; void formation during freezing; TES mass; ground testing to prove zero g operation | •TES design and manufacture |
| Advanced STE SD | •Concentrator mass, ease of deployability, and surface smoothness | •Reflective concentrator design |
| | •Integration of PCU and receiver | •Integrated unit testing |
| | •TES canister manufacturing techniques; void formation during freezing; TES mass; ground testing to prove zero g operation | •TES design and manufacture |
| | •Heater head life of Stirling engine, Stirling alternator life, engine efficiency | •Stirling engine long life superalloy materials, superalloy joining technologies, alternator materials, high efficiency alternator, and higher temperature operation |

TABLE 2-4. SUMMARY OF KEY ISSUES AND TECHNOLOGY GAPS (CONT'D)

| Technology | Issues | Technology Gaps |
|---|---|---|
| SP-100 TE | •High development cost and risk | |
| | •Safety of nuclear systems during operation | •Use of in-situ materials for shielding |
| | •Safety of nuclear systems during launch | |
| | •Protection of refractory materials in Martian environment | •High temperature, long life coatings<br>•Vacuum enclosures |
| | •High mass compared to other nuclear system options | •Dynamic SP-100 or TI reactor |
| | •Limited system power level | •Dynamic PCU |
| SP-100 CBC | •Safety of nuclear systems during operation | •Use of in-situ materials for shielding |
| | •Safety of nuclear systems during launch | |
| | •Protection of refractory materials in Martian environment | •High temperature, long life coatings<br>•Vacuum enclosures |
| SP-100 STE | •Safety of nuclear systems during operation | •Use of in-situ materials for shielding |
| | •Safety of nuclear systems during launch | |
| | •Protection of refractory materials in Martian environment | •High temperature, long life coatings<br>•Vacuum enclosures |
| SP-100 PRC | •Safety of nuclear systems during operation | •Use of in-situ materials for shielding |
| | •Safety of nuclear systems during launch | |
| | •Protection of refractory materials in Martian environment | •High temperature, long life coatings<br>•Vacuum enclosures |
| Driver Fuel In-core TFE Reactor | •TFE life | •In-reactor TFE and cell tests<br>•High strength emitter materials |
| | •Radiator mass | •High temperature C-C metal lined heat pipe development (liquid metal working fluid) |
| | •Safety of nuclear systems during operation | •Use of in-situ materials for shielding |
| | •Safety of nuclear systems during launch | |
| | •Effect of radiation on PP&C | •Radiation hardened components |

TABLE 2-5. SUMMARY OF KEY ISSUES AND TECHNOLOGY GAPS (CONT'D)

| Technology | Issues | Technology Gaps |
|---|---|---|
| PEM RFC | •Limited life of moving parts | •Passive system<br>•Long life pumps, drivers, valves, and controls |
| | •Material compatibility | •Materials for use with high pressure oxygen, hydrogen, and wet gases |
| | •Cell temperature and moisture control | •Thermal control loops, passive internal fuel cell gas humidifiers, regenerative gas dryers |
| | •Oxygen in fuel cell water | •Internal deoxygenator in fuel cell |
| | •Water in electrolyzer gases | •Regenerative dryers |
| | •Radiator mass and size | •Higher temperature cells, carbon-carbon radiator, heat pump |
| | •Efficiency of electrolysis cell at higher pressure | •Tank pressure following |
| NaS Battery | •Cycle life | •Physical and chemical stability of alpha alumina seal and electrolyte, sealing technology for tubesheet to cell case |
| | •High operating temperature | •Low mass carbon-carbon heat pipe radiator, heat pipe working fluid |
| | •Safety | •Battery casing design |
| GaAs-GE/CIS PV array/PEM RFC | •Large array area for Martian applications | •Higher efficiency top cell, robotic or automatic deployment, thin film arrays |
| | •Number of cells | •Increased cell size, higher efficiency top cell |
| | •Cell cost | •Mass production techniques |
| | •Operating temperature fluctuation and extremes | •Design and test for appropriate environment, test for thermal extremes |
| | •Dust accumulation (lunar/Mars) | •Robotic removal system |
| | •PEM RFC | •See PEM RFC system |
| PV/NaS Battery | •PV array issues | •See PV/RFC system |
| | •NaS battery issues | •See NaS battery system |

## TASK 2.3 TECHNOLOGY PROGRAMS

Major present and past government programs were identified and described for PEM RFC (mobile planetary surface power), NaS batteries (mobile planetary surface power), near-term CBC DIPS (1133 °K), advanced STE DIPS (1300 °K), GaAs-Ge/CIS PV array/PEM RFC, GaAs-Ge/CIS PV array/NaS battery, Driver Fuel In-core TFE reactor, SP-100 TE, Dynamic SP-100 (CBC, STE, and PRC PCUs), near-term CBC SD, advanced CBC SD, and advanced STE SD power systems in Appendices A to K (see "Technology Assessment" sections). Potential programs are also described in detail in the appendices.

The present power system technology development programs are considered adequate to satisfy future power requirements. NASA assisted Rocketdyne in identifying these ongoing programs whether they exist at NASA or in industry.

## TASK 2.4 DEVELOPMENT PLANS

For the technologies identified in Task 2.3, development road maps were prepared to reflect important milestones and critical paths for completion of development. These roadmaps are intended to aid NASA in planning technology development for future space power applications. Each roadmap provides an estimate of the time needed to develop flight qualified hardware given the state-of-the-art (or expected SOA at start of advanced program), the required major development tasks, and the schedule for hardware development to flight readiness. The development goals are expressed in terms of NASA Technology Readiness Level (TRL).

The development plans were divided into component development, Ground Engineering System (GES) development or Full Scale System Development, Qualification Unit development (QU), and Flight Unit (FU) Development. Due to the limited nature of this effort, only major tasks were identified. Power systems were broken down into major subsystems for ease of description. Both subsystem and system development tasks were identified and described.

Near-term power system technology roadmaps were developed based on the current technology status. Advanced power system technology roadmaps were developed based on the expected status at the start of the program. For each technology, the status was first assessed for the component technologies and then for the systems. Component technologies actually developed may vary from that assumed during this study. They may be driven by the mission needs (i.e., launch timeframe, level of funding, acceptable risk level, power level, etc.). The impact of on-going development efforts on technology status was included, where applicable. Thus, the start time of the power system development will affect the duration required for system development (due to prior component and ground system development). The start time for any technology development will depend on future mission requirements and the available funding.

Description of each roadmap includes discussion of the system concept and any necessary changes in development effort due to the launch date. Major subsystems in the system which differ significantly from previously proposed configurations are addressed separately in more detail. In particular, performance enhancement, challenges to fabrication, and long term operability are discussed. Major development (technical, cost, and operational) issues for each power system are addressed at both subsystem and system levels.

The current state-of-the-art (or expected SOA at program start) was assessed for each power system and major subsystem using the NASA Technical Maturity scale shown in Table 2-6. Overall program plans for each power system were developed to address all major technology issues involved with subsystem development, testing, fabrication, and launching. Development time for system integration to insure satisfactory system performance was also considered. The results of the technology assessment and development plan study are summarized in Tables 2-7 through 2-9. This table includes estimated development time and technology readiness levels.

TABLE 2-6. NASA TECHNOLOGY READINESS LEVELS

| Level | Evaluation |
|---|---|
| 1 | **Basic principles observed and reported**<br><br>The earliest stages of basic research, where physical principals are established |
| 2 | **Technology concept and/or application formulated**<br><br>Basic concepts are incorporated into concepts for hardware or software, and research begins to determine the feasibility of the applications. |
| 3 | **Analytical and experimental critical function and/or characteristic proof-of-concept**<br><br>Critical functions are proven for hardware and software either by analysis or experiment. |
| 4 | **Component and/or breadboard validation in the laboratory**<br><br>Breadboard hardware and software concepts are fabricated and validated in a laboratory environment against predetermined performance objectives. |
| 5 | **Component and/or breadboard demonstration in a relevant environment**<br><br>Breadboard hardware and software are tested in an environment that is relevant to proving the technologies will operate in the operational environment of the projected mission application. This may include, if required, flight research and validation. |
| 6 | **System validation model demonstrated in a simulated environment**<br><br>The breadboard hardware and software are integrated into a system validation model and tested in a simulated operational environment to study the interactions between the different components. |
| 7 | **System validation model demonstrated in space**<br><br>A system validation model, incorporating various technology components and breadboard subsystems, is demonstrated in space. |
| 8 | **Flight-qualified system**<br><br>System has been reconfigured for flight conditions. Performance and life testing have been satisfactorily completed. |
| 9 | **Flight-proven system**<br><br>Safety and acceptance testing of flight systems has been completed. Flight system has been successfully utilized in space for a complete mission. |

TABLE 2-7. SUMMARY OF TECHNOLOGY ROADMAP RESULTS

| System or Subsystem Technology | Current Technology Readiness Level (7/92) | Program Start Estimated Technology Readiness Level | Development Time* (yrs) |
|---|---|---|---|
| Near-term CBC DIPS | | | 6 |
| GPHS modules | 9 | | |
| HSU (RHRS, MFI, gas containment) | 4 | | 2.75 |
| CBC PCU | 5-6 | | 2.75 |
| Radiator | 6 | | 1.25 |
| PP&C | 5 | | 2.25 |
| Advanced STE DIPS (1300 °K)** | | | 4.75 |
| GPHS modules | 9 | 9 | |
| HSU (RHRS,MFI, gas containment) | 4 | 9 | 1 |
| STE PCU | 3 | 6 | 1 |
| Radiator | 3 | 6 | 1 |
| PP&C | 5 | 6 | |
| Near-term CBC SD | | | 6 |
| Concentrator | 5 | | 2 |
| Receiver/TES | 5 | | 2 |
| CBC PCU | 5-6 | | 2 |
| Radiator | 6 | | 2 |
| PP&C | 5-6 | | 2 |
| Advanced CBC SD | | | 7 |
| Concentrator | 3 | | 2.5 |
| Receiver/TES | 3 | | 2.5 |
| CBC PCU | 5-6 | | 2 |
| Radiator | 3-4 | | 1 |
| PP&C | 5-6 | | 2 |
| Advanced STE SD*** | | | 7 |
| Concentrator | 3 | 6 | 1.5 |
| Receiver/TES | 3 | 6 | 1.5 |
| 1050 °K STE PCU | 4 | 6 | 1.5 |
| Radiator | 3-4 | 6 | 1.5 |
| PP&C | 5-6 | 6 | 1.5 |

*To launch for systems; to TRL 5 for components.
**Assumes prior development of CBC DIPS.
***Assumes prior development of near-term CBC SD system.

TABLE 2-8. SUMMARY OF TECHNOLOGY ROADMAP RESULTS (CONT'D)

| System or Subsystem Technology | Current Technology Readiness Level (7/92) | Program Start Estimated Technology Readiness Level | Development Time* (yrs) |
|---|---|---|---|
| SP-100 TE | | | 13.5 |
| Reactor/Primary Loop | 3 | | 7 |
| TE PCU | 3 | | 7 |
| Radiator | 3-4 | | 6 |
| PP&C | 4 | | 4.5 |
| SP-100 CBC** | | | 10.5 |
| Reactor/Primary Loop | 3 | 6 | 2 |
| 1300 °K CBC PCU | 4 | 4 | 3 |
| Radiator | 3-4 | 6 | 2 |
| PP&C | 4 | 6 | |
| SP-100 STE** | | | 9.5 |
| Reactor/Primary Loop | 3 | 6 | 2 |
| 1300 °K STE PCU | 3 | 6 | 2 |
| Radiator | 3-4 | 6 | 2 |
| PP&C | 4 | 6 | |
| SP-100 PRC** | | | 13.5 |
| Reactor/Primary Loop | 3 | 6 | 2 |
| 1300 °K PRC PCU | 3 | 3 | 6 |
| Radiator | 3-4 | 6 | 2 |
| PP&C | 4 | 6 | |
| Driver Fuel In-core TFE Reactor | | | 7.5 |
| Reactor and Heat Transport | 3 | | 2 |
| TFE | 4 | | 2 |
| Radiator | 4 | | 2 |
| PP&C | 4 | | 2 |

*To launch for systems; to TRL 5 for components.
**Assumes prior development of SP-100 TE power system.

TABLE 2-9. SUMMARY OF TECHNOLOGY ROADMAP RESULTS (CONT'D)

| System or Subsystem Technology | Current Technology Readiness Level (7/92) | Program Start Estimated Technology Readiness Level | Development Time* (yrs) |
|---|---|---|---|
| PEM RFC | | | 6.75 |
| Fuel Cell Stack | 3.5 | | 3.25 |
| Electrolysis Cell Stack | 4 | | 3 |
| Active Thermal Management | 3 | | 3.5 |
| Water Management | 4 | | 3 |
| Reactant Storage Tanks | 5 | | 2.25 |
| PP&C | 5 | | 2.25 |
| NaS Battery | | | 7 |
| Battery Subsystem | 4 | | 3 |
| Thermal Management Subsystem | 3 | | 3.5 |
| PP&C | 5 | | 2.25 |
| GaAs-Ge/CIS PV Array/RFC | | | 6.75 |
| GaAs-Ge/CIS PV Array | 5 | | 2.25 |
| PEM RFC | 3.5 | | 3.5 |
| PP&C | 5 | | 2.25 |
| GaAs-Ge/CIS PV Array/NaS Battery | 3.5 | | 7.00 |
| GaAs-Ge/CIS PV Array | 5 | | 2.25 |
| NaS Battery | 3.5 | | 3.5 |
| PP&C | 5 | | 2.25 |

*To launch for systems; to TRL 5 for components.

## TASK 3.0 UPDATE OF MISSION/POWER REQUIREMENTS CODE

The purpose of this task was to convert and enhance the mission/power requirements code previously developed in the Space Station Evolutionary Power (SSEP) Technology Study (Ref.1) from an IBM PC class computers to an Apollo DN3000/4000 class workstation. The code conversion provides NASA with a capability equivalent to the current PC version of the requirements code in basic approach, but with a broader and faster applications base. The Apollo workstation was selected for this conversion due to the large quantity of data and the need for computational speed.

The first version of the mission/power requirements code (referred to as the RBASE code) operates on an IBM PC class computer or compatible. The RBASE code provides an automated method for determining the power requirements and effective utilization, implementation, and storage/retrieval of the very broad power requirements. It was used to generate the timeline and resource profiles for the three mission scenarios defined in the SSEP Technology Study covering more than 800 activities grouped into 75 platforms.

The approach used for determining and evaluating power requirements in the SSEP Study is outlined in Figure 3-1. In this figure, the first three blocks, scenario definition, activity identification and characterization, and platform branching analysis are all performed manually. First a scenario is defined in terms of general purpose and goals. Activities are then identified and characterized to meet these goals. The activities are then branched to distinct platforms. Platform branching is the assignment of environmentally compatible and co-located activities to physical platforms. The total power requirements for the activites grouped on such a platform will be met by a single power system for the platform.

The resulting data is then used in conjunction with the RBASE code to produce the platform power requirements. The scheduling of the activities into timelines (i.e., timeline development) was performed using "Microsoft Project Management" software and the resource quantification (i.e., summation of activity requirements) was performed using "RBASE System V" relational database software (Refs. 6 & 7). Results and data from the PC version of the requirements code can be found in the SSEP Final Report (Ref. 1).

The new version of the mission/power requirements code was developed using TREES-pls and FOREST-pls software available from AVYX Incorporated and is operational on an Apollo DN3000/4000 class workstation (Ref. 8). The name given to this version of the timeline/resource profile software was ESPPRS (Evolutionary Space Power and Propulsion Requirements System). ESPPRS incorporates the scheduling, resource quantification, and output generation functions performed previously by two software packages into a single integrated program. Therefore, all data related to a scenario is entered through a single interface to the ESPPRS program.

The principal enhancements provided by the ESPPRS version of the timeline/resource profile software include:

1. Integration of the scheduling, resource quantification, and graphical output capabilities of the previous version into a single code;
2. Faster turnaround for power requirements results;
3. Additional capability to perform nodal analyses of resources (see Appendix L);
4. Simplified user interface.

The input to the ESPPRS program is the data describing a set of activities which comprise a particular mission or scenario. This data, entered on a per activity basis, includes an activity description, activity name, platform assignment, power requirement, initial mass requirement, resupply mass requirement, personnel requirement, and platform assignment. This data is then loaded into the ESPPRS program and the schedule feature exercised to produce a set of timeline profiles and aggregate resource requirement plots for the mission or scenario. Once scheduled, timeline and resource profiles can be viewed or printed. If changes to the resource or timeline results are desired, activities can be unscheduled, modified, and then rescheduled. Nodal analyses can also be performed by assigning multiple platforms to nodes (e.g., different locations - LEO, GEO, Mars Orbit) and then summing the resource requirements on a per node basis.

Figure 3-2 presents a summary of the output (resource profiles and timeline schedules) for the mission/power requirements program. Examples of the ESPPRS code output are provided in Appendix L.

Verification of the ESPPRS version of the mission/power requirements code was performed by loading the data set for the Level 3 scenario of the SSEP Study and creating timeline and resource requirement reports and manually checking these against previous reports generated by the RBASE version of the mission/power requirements code. This ESPPRS code was demonstrated at NASA-LeRC in December, 1989 and a final version was subsequently transferred to NASA personnel. Information on the function and use of the ESPPRS software is provided in Appendix L - ESPPRS User's Guide.

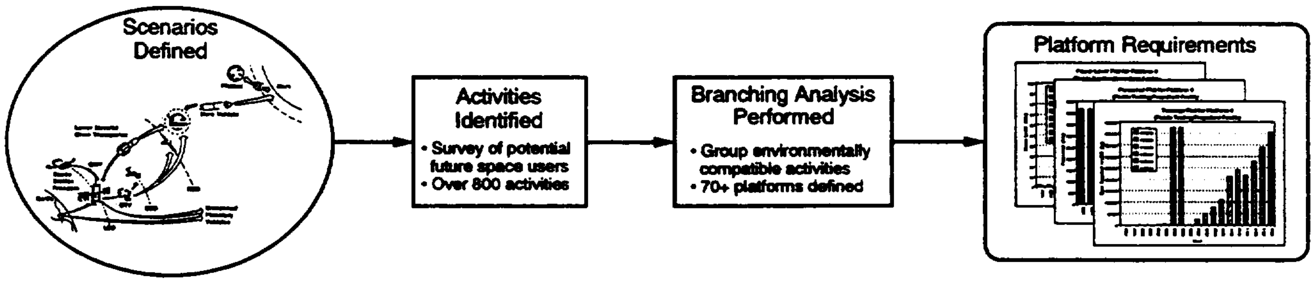
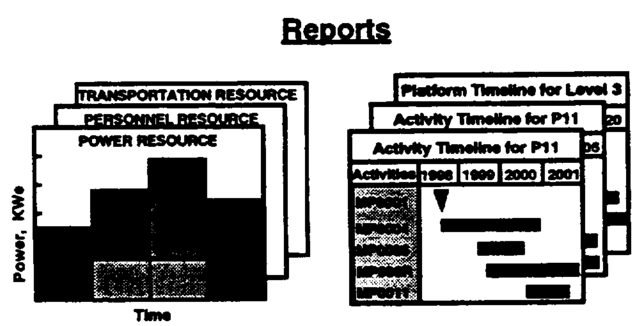



Figure 3-1. Power Requirements Methodology




- **Resource Profiles**
  - **Power requirements**
  - **Personnel requirements**
  - **Mass requirements**
  - **Profiles available for each platform**
- **Timelines/Schedules**
  - **Timelines of activities on a platform**
  - **Timelines of activities in a scenario**
  - **Timelines of platforms in a scenario**
- **View of facilities & total resources needed for a scenario**

Figure 3-2. Mission/Power Requirements Code Outputs

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16. Abstract

A comprehensive scenario of future missions was developed and applicability of different power technologies to these missions was assessed. Detailed technology development roadmaps for selected power technologies were generated. A simple methodology to evaluate economic benefits of current and future power system technologies by comparing Life Cycle Costs of potential missions was developed. The methodology was demonstrated by comparing Life Cycle Costs for different implementation strategies of DIPS/CBC technology to a selected set of missions.

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